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MINERALOGY

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MINERALOGY

AN INTRODUCTION TO THE SCIENTIFIC STUDY OF MINERALS

BY

SIR HENRY A. MIERS

M.A., D.Sc., F.R.S.

FORMERLY WAYNFLETE PROFESSOR OF MINERALOGY

242348

SECOND EDITION

REVISED BY

H. L. BOWMAN

M.A., D.Sc.

WAYNFLETE PROFESSOR OF MINERALOGY IN THE UNIVERSITY OF OXFORD AND FELLOW OF MAGDALEN COLLEGE

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FROM THE PREFACE TO THE FIRST EDITION

The student will not find in the following pages any systematic account of the modes of occurrence of minerals, their geological distribution, their origin, their alterations, or their artificial reproduction, although these constitute the most important and, perhaps, the most interesting section of Mineralogy proper. There are no chapters upon these subjects because, in my opinion, they deserve to form a separate volume, and cannot be treated adequately in a volume dealing with the characters and properties of minerals. The essential characters of a mineral, moreover, are quite independent of its source or previous history, and may well be made the first and separate object of study.

In the description of mineral species an attempt is made to select for the student all that he requires for an elementary acquaintance with the subject. The species described are those which he will find in all museums, and most of them he may collect for himself. The customary lists of localities are replaced by a description of a few typical occurrences for each important species ; by a careful study of the corresponding specimens the beginner should obtain the information which will enable him to pursue the subjects of geological and chemical mineralogy with some previous knowledge of minerals. The few angles given are generally only such as are sufficient for the calculation of the axial ratios or for simple exercises in the calculation of indices.

In the discussion of optical characters, the introduction of two ellipsoids may appear unnecessary and even confusing; the Fresnel ellipsoid has been introduced in order to avoid incorrect statements about optic axes, but it will be found that the indicatrix is the only ellipsoid subsequently employed.

It cannot be too strongly impressed upon the student at the outset that scientific mineralogy is based upon accurate measurements and determinations, and, accordingly, it is to the intelligent use of the goniometer and microscope that his attention is mainly directed in the following pages.

HENRY A. MIERS.

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PREFACE TO THE SECOND EDITION

In the new edition the original plan of the book, and so far as possible the original text, have been retained, with such changes and additions as seemed desirable in view of advances in the subject or to make the book more useful to students.

In the chapter on the optical properties of crystals the idea of the wave-surface has been introduced, as it probably enables a student to form a clearer picture of the passage of light through a crystal than he can gain from the ellipsoids alone.

The section on crystal structure has been somewhat enlarged and a chapter added on X-ray analysis.

A considerable number of new figures have been added, and many of the old ones redrawn, while the whole of the text has been carefully revised.

My thanks are due to Sir Henry Miers, Dr. L. J. Spencer, and other friends for notes of corrections required, and to Dr. T. V. Barker for suggestions regarding the chapters on chemical properties and isomorphism.

The drawings for many of the new figures have been made by Mr. R. C. Spiller, University Demonstrator in Mineralogy, and I am further indebted to him, as well as to my wife, for help in the revision of the proofs and the preparation of the index.

H. L. BOWMAN.

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INTRODUCTION

1. **A Limitation of the Term "Minerals."**—By the term "Minerals" are generally understood the materials which constitute the solid crust of the earth; such materials may consist either of inorganic substances, such as granite, or of organic substances, such as coal. In the latter case their study will involve some acquaintance with the methods of organic chemistry. Further, they may either, like granite, have originated quite independently of living animals or plants, or they may, like coal or chalk, have been produced through the life or the decay of such organisms. In the latter case their study will involve some acquaintance with biology.

In the present volume it is proposed to exclude from consideration the whole class of organic materials and also those which, though inorganic in their composition, have been produced by organic agencies. The latter class comprises the materials which have been secreted by or have formed part of living organisms. The above limitation, therefore, relieves us of the necessity of taking any account of vital processes in our study of minerals, or of entering into any biological problems. Chalk, pearls, and diatomaceous earth, though inorganic in composition, will be excluded as consisting of the shells, secretions, or skeletons of living organisms; coal, amber, and guano will be excluded on account of their organic composition as well as their mode of origin; petroleum will be excluded on account of its organic composition, although its origin may not have been connected with the life or decay of any organism.

There is no logical reason why the gases and liquids of the earth's crust should not be described in a treatise on Mineralogy, together with the solid materials, since the solid, liquid, or gaseous condition of a substance depends merely upon the temperature and pressure to which it is subjected; indeed the ice of the Polar regions has every claim to be regarded as a *solid* portion of the earth's crust. The only inorganic liquids which necessarily find a place in any complete survey of the mineral kingdom are mercury and water, but these possess little special interest in relation to the general study of minerals, and in fact their mineralogical description is incomplete unless account be taken of the characters which they exhibit when solid, so that the word *solid* has been used above in referring to the crust of the earth.

2. **Of the Essential Properties of Minerals.**—Those pieces of mineral

matter which are found to possess the same properties are said to belong to the same "kind" of mineral; the number of mineral kinds is very limited; only about 1000 are known which are really definite; and all the rocks and stones of the earth's crust which are not simple minerals are made up of some of these kinds mixed in various proportions. Under whatever conditions minerals are found, and in whatever way they have been produced, certain properties belong to each, and are shown by every specimen of it, and it is by these properties that each kind of mineral is accurately defined.

It is therefore necessary to study first the properties of each mineral, and the object of the present volume is to indicate how this is effected. The exact study of minerals has only been developed in recent years, through the discovery of methods by which their properties may be readily and accurately determined. Previously it was customary to distinguish them by their colour, lustre, hardness, fracture, and by superficial characters, some of which, though easily observed, are not capable of exact measurement, while others are variable in different specimens of the same mineral. In the present state of our knowledge, no one property in itself is sufficient to distinguish a given mineral from all others; it is highly probable that when means have been discovered of determining the chemical constitution completely, in the sense in which it is possible for some of the carbon compounds of organic chemistry, this alone will be sufficient, and all the other properties will be deducible from it; but at present we are forced to employ at least two properties, preferably the chemical composition (percentage composition, see p. 223) and the crystalline form; these two, when completely known, are necessary and sufficient for the definition and determination of any mineral.

Two or more minerals may have the same chemical composition (*e.g.* rutile and anatase) and yet differ in all their other properties; two or more minerals may have the same form (*e.g.* salt and fluor) and yet differ in all other respects; but if they possess the same composition *and* the same form, they will of a certainty possess in common also other properties —which we may henceforth call the "essential" properties—and will therefore be said to belong to the same mineral kind.

Those characters of minerals which vary among different specimens possessing the same form and composition are not essential: far too great importance has generally been assigned to them in the definition and identification of mineral kinds; such characters are "habit," colour, and the form and structure of mineral aggregates.

3. **Of the Two Sorts of Essential Properties.**—The essential properties of minerals, as of all other substances, are of two sorts.

Firstly, those which do not involve the idea of direction, but represent the nature of the substance in the aggregate; such are the density, the specific heat, the chemical composition; and, secondly, those which are measured in some definite direction.

Take, for example, the properties relating to heat; the specific heat of a body is accurately measurable, but not in any particular direction; a piece of rock crystal has the specific heat 0·1881, but it is meaningless

to speak of a direction of specific heat. On the other hand, the (linear) expansion of a body caused by a given rise of temperature can be measured in a definite direction.

Hence a distinction may be made between the "general" properties and the "directional" properties; to the former belong the density, the specific heat, the temperature of fusion, and the chemical composition; to the latter belong the cohesion, the elasticity, and a number of the optical, thermal, electric and magnetic properties, as well as the crystalline form.

4. **Of the Two States in which Minerals occur.**—When the directional properties of minerals are examined, it is found that a specimen may behave in one of two ways. In a uniform piece of a single mineral either (1) every one of its directional properties has the same value in all directions, or (2) some of them vary with the direction.

In the former case the mineral is said to be " amorphous," and in the latter it is said to be " crystallised."

For example a sphere (Fig. 1) cut out of rock-crystal whose natural shape is shown in Fig. 2, when heated uniformly, becomes converted into

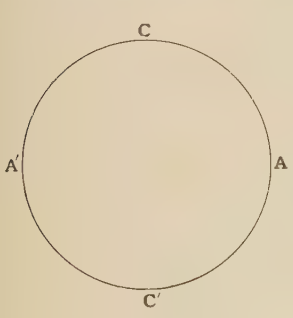


Fig. 1.

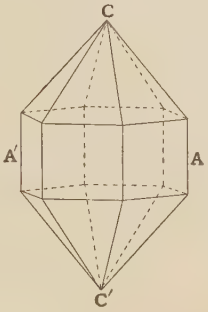


Fig. 2.

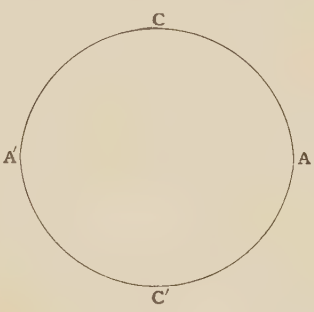


Fig. 3.

the oval figure or spheroid of Fig. 3, in consequence of the unequal expansions in different directions, and these might be ascertained by measuring the exact dimensions of the spheroid. It would be found that the expansion of the rock-crystal along such directions as AA′ has been about twice as great as that along CC′.

Opal, on the other hand, which has a composition not very different from that of rock-crystal, differs conspicuously from it in being amorphous. Thus a sphere of opal does not, like rock-crystal, become a spheroid when heated, but remains a sphere, because its expansion is the same in all directions.

An amorphous mineral has no characteristic shape. Each crystallised mineral has a characteristic shape, and a mineral exhibiting its characteristic shape is called a " crystal." Fig. 2 is the characteristic shape of rock-crystal.

But minerals when crystallised do not always occur in such separate single crystals. The behaviour of ordinary sugar illustrates the various possibilities. If it be allowed to separate slowly from solution, sugar

makes its appearance in separate tablets, each of which is a single "crystal." But ordinary loaf-sugar is neither amorphous nor a crystal; the properties of a lump of such sugar are apparently the same in every direction, but the lump is not amorphous for it is not really homogeneous; it may be broken up into a number of minute fragments, each of which is part of a single crystal. Hence it is evident that a crystallised mineral need not always show its characteristic form, for it may be a mass consisting of a number of crystals so aggregated together as to interfere with each other and obliterate their characteristic forms by mutual contact. Such a mass is said to be "crystalline." Fig. 4 shows the appearance presented under the microscope by a slice of crystalline quartz (or quartzite)—the same material which in the form of Fig. 2 is known as rock-crystal. It is generally necessary, if a mineral behaves like an amorphous substance, to examine it with the microscope in order to ascertain whether it is not really a mass of minute crystals, in which case it is termed "microcrystalline."

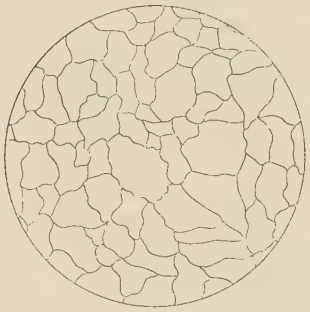


Fig. 4.—Section of Quartzite.

Hence, finally, the two states in which a mineral may occur are—

(1) "Crystallised," when the mass as a whole, or each grain of which it consists, exhibits properties which are different in different directions but the same in parallel directions.

(2) "Amorphous," when it does not exhibit any properties which vary regularly with the direction.

By far the larger number of minerals are crystallised, or at least crystalline, though their crystalline texture may be so fine-grained as to be only discernible under high magnification, as in chalcedony. Those few which are really amorphous are probably colloidal "gels" (*e.g.* opal).

A mineral can only exhibit these regularly varying directional properties when it is crystallised. Without them it may be difficult to distinguish between two different minerals which have the same composition, since the general properties only give the nature of the substance in the aggregate, and may not differ sufficiently for the purpose, just as it may be difficult to distinguish between two isomers having nearly the same reactions and melting point, unless they can be obtained in crystals.

It is reasonable to suppose that the particles of which a crystal consists are placed side by side in some regular arrangement, like the men in a battalion of soldiers; whereas in an amorphous substance they have no regular order. Without some such hypothesis it is impossible to understand how the properties of a crystal vary regularly with the direction. It is, moreover, in complete accordance with what we know of the growth of crystals; when a substance crystallises in passing from solution or from the molten condition to the solid state the crystal increases in size by the constant addition of fresh material to the surface; this is totally unlike the

growth of living matter, and can only be explained as due to the deposition of layer after layer of minute particles; and since neither the characteristic form nor the physical properties are changed as the crystal grows, it must be supposed that the particles continue to be deposited with the same regular arrangement.

Since the crystalline characters as well as the chemical composition are necessary for the complete definition of a mineral, the crystallised condition is obviously the only one in which a mineral can be completely investigated, although it may also exist in the liquid state.

5. **Of the Scientific Study of Minerals.**—The history of mineralogy began with the development of mining and of the decorative arts; in the search for useful and ornamental materials the nature and the properties of the more common minerals were discovered.

The metalliferous nature of certain ores, the brilliancy and hardness of certain precious stones, were thus brought to light; the use of some minerals as sources of useful products, such as lime, plaster of Paris, glass, etc., of others as pigments, of others again for their medicinal virtues, led to the study of their properties. It became necessary, further, to investigate their modes of occurrence and the characters by which they might be recognised in order that it might be known where they were likely to be found, and how they might be distinguished when found.

About the beginning of the last century the time came, just as it comes in the history of every science, when mineralogy became a study carried on for its own sake, in a systematic way, with the object of discovering the general laws which it illustrates.

Mineralogy is not, like physics or chemistry, devoted to the study of particular laws, but rather of particular materials, and scientific mineralogy involves the accurate investigation of minerals in all their aspects—not merely of the qualities which are useful for industrial and artistic applications. It is therefore the function of the mineralogist to examine every portion of the earth's crust; to determine all the properties of every mineral, whether common or rare; to classify and compare these minerals with the purpose of ascertaining how they resemble each other, and how they differ. With this wide object in view he leaves no method of research untried; and the study of purely scientific mineralogy has consequently, like all scientific research, discovered many useful and suggestive properties which would have been overlooked in any mere attempt to satisfy present needs. It has thus contributed very largely to chemistry, physics, and geology—to chemistry, for example, by the discovery of new elements and compounds; to physics by the investigation of the optical and electrical characters of such minerals as Iceland spar, rock-crystal, and tourmaline; to geology by the microscopical identification of the rock-forming minerals necessary in order to understand the genesis of rocks.

One important branch of scientific mineralogy is the study of the modes and places of occurrence of minerals, their origin and the changes to which they are subject. This is to a large extent an entirely independent subject, except in so far as it throws light upon the nature

of the minerals themselves; it is, moreover, a study which should succeed that of the essential properties of minerals, for the essential properties do not vary with the origin or the modes of occurrence; the chemical composition and the form are constant for each mineral wherever, whenever, and however it may have originated.

For this reason the present volume deals almost exclusively with the essential properties of minerals and the methods by which they are investigated; and will only mention their natural modes of occurrence, their origin, and their alterations so far as they contribute to our knowledge of the properties.

From what has been said above it will be clear that the properties of minerals could only be adequately investigated in crystallised specimens, and that the accurate and complete study of minerals could only be established with the aid of a science of crystallography.

Further, the physical and geometrical properties of crystals can be investigated without their destruction, whereas their chemical composition can only be ascertained by the analysis or destruction of the material; it is therefore natural to begin our study of the essential properties with the former, and to learn how to investigate the nature of a mineral as far as possible before destroying it.

As the Abbé Haüy (who was the originator of crystallography as a science) remarks in his *Traité de Minéralogie* (1801)[1]—"S'il est des cas où le minéralogiste ne peut se dispenser de dire au chimiste : *Apprenez-moi ce que vous venez d'analyser*, il en est d'autres où le chimiste, pour être prudent, doit dire au minéralogiste : *Apprenez-moi ce que je vais analyser*."

Accordingly we proceed at once to the geometrical and physical properties of minerals before considering their general properties and the nature of their various kinds.

[1] Vol. i. p. 166.

PART I

THE PROPERTIES OF MINERALS

BOOK I

THE CRYSTALLINE PROPERTIES

CHAPTER I

THE CRYSTALLINE FORM OF MINERALS

1. **Crystals.**—Most substances when allowed to solidify slowly, either from solution, or from the molten condition, or from a state of vapour, assume characteristic forms, enclosed by plane surfaces; these are called "crystals"; the substance in solidifying is said to "crystallise," and the plane surfaces of a crystal are called its "faces." Familiar instances of the different modes of crystallisation are: (1) the crystals of alum or borax deposited from solutions of those substances when the water in which they are dissolved is allowed to evaporate slowly; (2) the crystals of sulphur which are found encrusting the sides of a crucible containing fused sulphur when a portion of the cooling mass is poured off; (3) the brilliant crystals which are formed on the sides of a bottle containing camphor; these last are due to the gradual volatilisation of the camphor and its condensation from a state of vapour.

Crystals may also be formed in any of these three ways when a substance originates from the combination or decomposition of other substances; as, for example, when a crystalline precipitate is produced by the mixture of two solutions.

Most minerals are, sometimes at least, found as crystals; quartz or "rock-crystal" occurs in the form of a hexagonal prism terminated

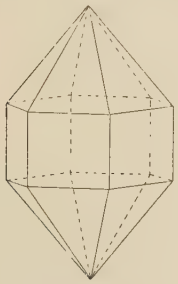


Fig. 5.—Quartz.

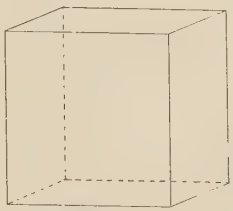


Fig. 6.—Fluor-spar.

by hexagonal pyramids (Fig. 5); fluor-spar in cubes whose six faces are squares (Fig. 6); spinel in regular octahedra whose eight faces are

equilateral triangles (Fig. 7); garnet in "rhombic dodecahedra" whose faces are twelve rhombs (Fig. 8); each mineral has its own characteristic crystalline form.

As was said above, the form of a crystal is supposed to be due to the orderly arrangement of the particles, just as the form of a military square is due to the orderly arrangement of the men; in solution, and in the liquid or gaseous condition the particles are supposed to be free to move in all directions; in the solid they are supposed to be confined by the constraining action of the neighbouring particles, so that each can only move to a limited extent about a fixed position and may be regarded as practically stationary. The essential form of the crystal is, as might therefore be expected, found to depend upon the nature of the substance and not upon the conditions under which it crystallised. A solution of

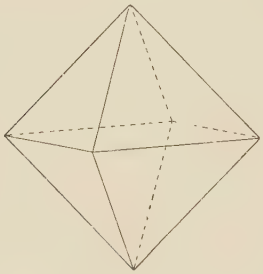


Fig. 7.—Spinel.

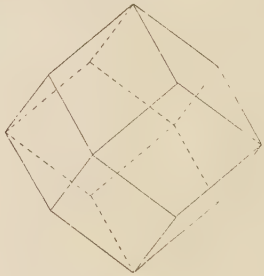


Fig. 8.—Garnet.

borax cannot yield crystals having any other than the form characteristic of borax, neither can fluor-spar or garnet assume spontaneously the form of quartz or calcite.

2. **Constancy of Angle.**—Although the crystalline form of a given mineral is characteristic and constant, it must not be supposed that the crystals always present the same appearance to the eye. Spinel has just been said to crystallise in "regular octahedra." Now the regular octahedron of geometry is the figure whose faces are eight equal equilateral triangles; it is the only figure which can be constructed from eight such triangles, and if cut across in a plane perpendicular to any one of its edges the section would have the angle 109° 28′; yet the octahedron of spinel, though it always has eight faces, may assume a variety of irregular forms according to the relative sizes and shapes of its faces, as shown in Figs. 9 and 10. How then can the spinel crystal be called an octahedron? A closer examination will show that these variations in form are due merely to differences in the *sizes* of the faces; in both figures the directions of the faces are unchanged, for they are parallel to those of the regular octahedron represented by the dotted lines; and a section perpendicular to any one of the octahedron-edges would still give the angle 109° 28′. Both Fig. 9 and Fig. 10 are called regular octahedra, because their faces are parallel to those of the regular octahedron, and make with each other the angles of the regular octahedron,

although the faces are not all of the same size. They may be called " misshapen " octahedra. Striking examples of such misshapen figures among minerals are the delicate fibres of cuprite, known as chalcotrichite, which

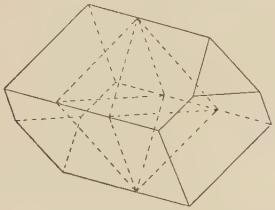


Fig. 9.

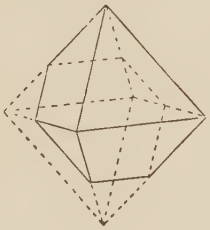


Fig. 10.

Misshapen Octahedra.

are in reality elongated cubes of great length in comparison with their breadth. In misshapen crystals the variations from the ideal figure are found to be due to the conditions under which the crystals are formed. If, for example, a growing crystal be so situated that it can grow more readily in one direction than in others, it will become elongated in that direction (Fig. 9). The flattened crystals of alum frequently formed on the bottom of the crystallising-vessel have the six-sided tabular form of Fig. 10.

The form which a crystal assumes by virtue of the *relative sizes* of its faces is called its "habit"; thus an octahedron may assume a "tabular" (Fig. 10) or " prismatic " habit (Fig. 9) according as it becomes a tablet or a prism by the enlargement of two or of four of its faces; but variations of habit do not indicate any change in the real form of a crystal.

The constancy of angle, notwithstanding variations of habit, was proved in the case of quartz in 1669 by Nicolaus Steno, the famous Danish physician, geologist, and theologian; he found on making sections of the crystals that the angles of corresponding sections were the same however the crystal might be misshapen. This was the first successful attempt to discover any law regulating the forms of crystals. A century later Romé de l'Isle laid the foundations of crystallography by examining an enormous

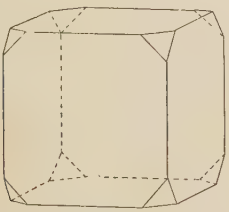


Fig. 11.

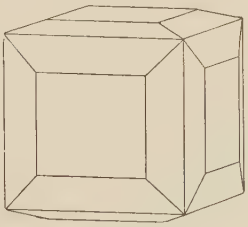


Fig. 12.

Cubes with secondary faces.

number of minerals and other crystallised substances; he was able to show that each substance could be referred to a certain characteristic

form which he called the " primitive form," and that all crystals of the substance either had the constant angles of the primitive form, or consisted of the primitive form modified by other so-called secondary faces upon its corners and edges. Thus, the cube is the primitive form of fluor-spar, and crystals of fluor-spar are either simple cubes or have secondary faces derived from the cube in a regular manner (Figs. 11 and 12).

3. **Use of Geometrical Methods.** — There are five " regular solids " known in geometry (octahedron, cube, tetrahedron, regular dodecahedron, icosahedron), each of which is bounded by a certain number of equal, equilateral, and equiangular faces. Of these figures the first three are to be found among crystals, but, as we have just seen, the corresponding faces of the natural crystal are not necessarily alike, either in size or shape.

There is, however, a sense in which they may be called "similar" faces ; thus all the planes of a cube of fluor are found not only to have the same mutual inclinations, but, further, to be identical in their *physical characters* ; they possess the same colour, lustre, and hardness ; they behave in the same way when exposed similarly to the action of the same agents, such as heat, light, and electricity ; they are similarly affected by the same solvents ; in this sense also the eight faces of an octahedron of spinel, or the twelve faces of a dodecahedron of garnet are *similar* faces.

Different faces of a crystal may differ in colour, brilliancy, smoothness, etc. (see Figs. 80, 505, 562), but those faces which are really similar are identical in these respects.

In order to discover which are the similar faces on a misshapen crystal all such physical characters must be taken into account. In fact it is evident that the study of crystals is not merely a branch of geometry ; to ascertain which faces are really similar it is necessary to examine not only their angular relations, but also their physical properties.

On the other hand, the study of the crystalline form of a mineral may be conducted by purely geometrical methods, if all the similar faces be represented by planes of identical shape and size ; in other words, when the crystal has been idealised into a geometrical figure in which *physical* similarity is indicated by *geometrical* similarity in shape and size. In this sense Fig. 7 is an ideal representation of both the spinel crystals of Figs. 9 and 10, for its eight faces are identical in size and shape, just as those of the spinel crystal are identical in their physical features. In the same way fluor-spar, whatever its habit, is said to crystallise in cubes when it is bounded by six *similar* faces at right angles to each other ; and garnet is said to crystallise in rhombic dodecahedra when it is bounded by twelve *similar* faces inclined at equal angles to each other. But it must not be forgotten that the ideal or geometrical figure is only a representation of the physical reality.

When a crystal has grown under uniform conditions it sometimes assumes almost exactly the perfect geometrical figure, all its similar faces being geometrically identical, *i.e.* having the same shape and size. Rhombic dodecahedra of garnet and octahedra of magnetite are often almost geometrically perfect.

4. **Cleavage.**—Of all the physical characters of a crystal, the curious property known as "cleavage" is one of the most important, and is the most easily observed. Many crystals, when struck with a hammer, or pressed with the blade of a knife or with a sharp point, break up by separating along certain planes. Mica (often wrongly called talc) and gypsum may be easily split into sheets of any desired degree of thinness. Diamond not only *crystallises* in octahedra (Fig. 7), but also always splits or "cleaves," when struck, along surfaces parallel to the eight faces of the octahedron: a fact of which the diamond-splitters and -cutters often take advantage. The octahedron cleaved out of a diamond crystal will not necessarily have all its faces of the same size, but it may be reduced to the ideal geometrical octahedron by flaking away slices parallel to the smaller faces until they are all made equal. The cleavage-planes are often perfectly smooth and have a brilliancy of surface like that of natural crystal faces, which cannot be exceeded by any artificial polish.

Since now any crystal of diamond can be split with *equal* facility along four planes inclined to each other at the angles of the regular octahedron, the resulting four plane surfaces, together with the four surfaces parallel to them, constitute the eight similar faces of a regular octahedron, and the diamond is said to have an "octahedral cleavage." If the four cleavages did not take place with equal facility they would not represent similar planes, and therefore could not belong to the *regular* octahedron. Further, it is found that the cleavage takes place parallel to the natural faces of the diamond crystal, and not to any other set of planes inclined to one another at the octahedron-angle.

Similarly a cube of galena can be split with equal facility parallel to all its three pairs of faces and may thus be subdivided into small cleavage-cubes; galena is therefore said to cleave parallel to the faces of the cube, or to have a "cubic cleavage" (*cf.* Fig. 37).

Cleavage had been observed at a very early date and was studied by Bergman (1773), but this property acquired a new importance in the researches of the Abbé Haüy of Paris (1784), who was the first to observe that all crystals of the same substance possess the same cleavage, and was led by this observation to a theory of crystal structure which explained all the known facts and first raised the study of crystals to the dignity of a science. His own account of the discovery is as follows[1]—"The fundamental idea of my whole theory was suggested to me by an observation which I made upon calcareous spar in six-sided prisms terminated by two hexagonal faces [see Fig. 13]. I had noticed that a crystal of this variety, having been detached by chance from a group, was broken obliquely across in such a way that the fracture presented a clean surface, having the lustre which may be recognised as Nature's polish [Fig. 14]. I then endeavoured to obtain from the same prism sections in other directions, and after several attempts succeeded in obtaining from each side of the prism three oblique sections [Fig. 15]; by new sections parallel to the first I removed from the centre of the prism a rhomboid precisely similar to Iceland spar [see

[1] *Essai d'une théorie sur la structure des crystaux*, p. 10.

Fig. 16]. Struck with this observation, I took other calcareous spars, . . . and I found in them the same rhomboidal kernel which had been yielded by the prism mentioned above. Similar trials made upon crystals

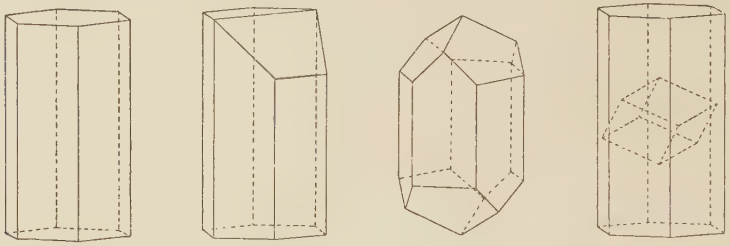


Fig. 13. Fig. 14. Fig. 15. Fig. 16.

The Cleavage of Calcite.

of several different kinds soft enough to be smoothly divided gave me kernels which had other shapes, but of which each was invariable in the same kind of crystal."

The theory of crystal structure which Haüy based on these observations is alluded to below (p. 21); at present we are only concerned with the fact that calcite has a characteristic cleavage which is not parallel to the hexagonal prism in crystals of that form.

In the octahedron of diamond and the cube of galena the cleavage was parallel to the natural faces of the crystal, but, as shown by Haüy's calcite, this is not necessarily the case. A crystal may have one form and its cleavage-figure may have another. Fig. 17 represents a cube of fluor-spar

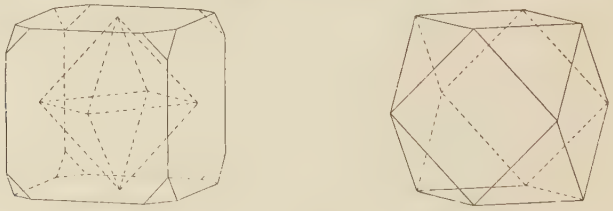


Fig. 17. Fig. 18.

The Cleavage of Fluor-spar.

of which the corners have been split off by cleavage; each corner has thus been replaced by a new triangular plane which has removed three equal lengths from the cube-edges meeting in the corner; this process may be continued by cleaving away more and more from each corner until the form of Fig. 18 is obtained; finally, if the cleavage be carried on so far that the new faces meet in points at the centre of each cube-face, the original crystal will be converted into the regular octahedron which is represented in Fig. 17 as inscribed in the cube. Hence in fluor-spar the octahedron can be obtained from the cube by cleavage, and this mineral is said to crystallise in cubes but to have an octahedral cleavage.

5. **Combinations.**—The crystal form of Fig. 18 consists both of cube- and octahedron-faces, and is called a " cubo-octahedron " ; such a figure may result not only from cleavage but also from natural growth ; fluor-spar, for example, usually crystallises in cubes, but may also crystallise in cubo-octahedra, each identical in form with a cubo-octahedron obtained by cleaving away the corners of a cube.

Crystals which combine two or more such simple figures are called " combinations " ; thus Fig. 17 is a combination of the cube and octahedron. Fig. 18 is the same combination, but the octahedron-faces are larger. In a combination of two or more figures the predominant figure is said to have its edges and corners " replaced " or " modified " by the smaller faces of the other figures.

In the language of Romé de l'Isle the predominant faces are those of the primitive-figure ; the others are secondary faces which modify its corners and edges. He found, for example, that fluor-spar could be referred to the cube as primitive figure, and that among the secondary faces of fluor-spar were to be found those of the octahedron.

6. **Symmetry.**—There are many ways of cutting an octahedron out of a cube, but it will be seen from Fig. 17 that the cleavage-octahedron supplied by Nature from a cube of fluor-spar is the only one which can be *symmetrically* derived from the cube ; its faces are parallel to those of the inscribed octahedron. This is found to be a universal law ; the cleavage-figure is always one which can be symmetrically derived from the crystal itself ; and, further, in any combination each figure always has its edges or corners symmetrically modified by the faces of the other.

Now a geometrical figure is symmetrical when every part of it is similar in form to one or more other parts ; the geometrical cube has eight similar corners, six similar faces, and twelve similar edges. In the same way the crystal cube has eight similar corners, six similar faces, and twelve similar edges ; here, as before, the word " similar " must be understood to mean identical in physical properties and in mutual inclinations, but not necessarily identical in shape or size.

If, then, a crystal of fluor-spar is really a cube, it must have the symmetry of the geometrical cube, and its eight corners must be identical in all their physical characters ; if one corner can be removed by cleavage along a single plane equally inclined to the cube-faces, the remaining corners must be capable of similar cleavage, and the cleavage-figure must be an octahedron. A crystal having the appearance of a cube, which could be cleaved upon one of its corners, but not upon all, would not be really a cube, for it would not have the physical symmetry corresponding to the geometrical cube.

It is the same with the growth of the secondary faces ; if one corner of a crystal cube is replaced by a face of the octahedron, all the corners must be so replaced, and the crystal becomes a complete combination of the cube and octahedron.

The simple law of symmetry which governs all the features of crystal growth may be thus stated : *similar parts of a crystal are similarly modified.* If certain secondary faces are present upon one corner or edge of

the crystal, precisely similar secondary faces will be found upon all the similar corners or edges.

It is this law which gives regularity and beauty to the manifold variety of forms belonging to a given mineral, and renders it possible to explain the most complicated and apparently capricious crystalline growths as symmetrically derived from a simple primitive figure.

The exact relations between the secondary faces derived from the primitive figure were discovered by Haüy, and will be explained below (p. 25), but it will already be clear that in any one mineral only certain figures can enter into combination. For example, calcite breaks up very readily by cleavage to give the rhombohedron of Fig. 19, and whatever may be the form of the crystal this same rhombohedron will be derived from it by cleavage, as shown in Fig. 39.

A frequent form of calcite (the variety common in Derbyshire and

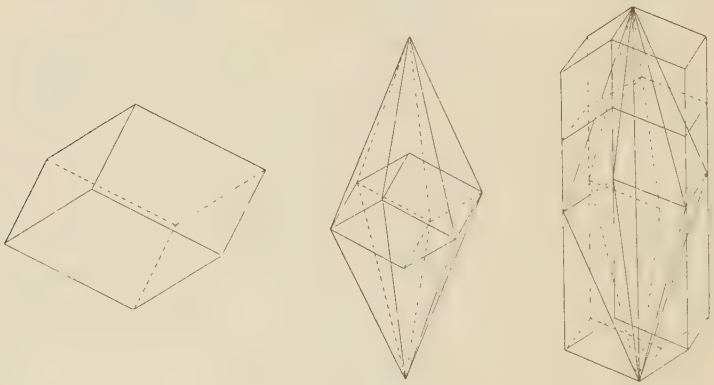


Fig. 19. Fig. 20. Fig. 21.

The Cleavage of Calcite.

known as " dog-tooth spar ") is that of Fig. 20, and the cleavage-rhombohedron is here represented as symmetrically inscribed within it. This rhombohedron is itself one of the forms in which calcite crystallises and is regarded as the primitive form ; Fig. 20 can be symmetrically derived from Fig. 19, but since it cannot be symmetrically derived from the cube, it can never occur either as a crystal or as a cleavage-form in any mineral which crystallises in cubes. Fig. 21, copied from Bergman, shows very clearly how far these facts had been recognised by him as early as 1773. The figure shows two crystals of calcite, a prism terminated by rhombohedron-faces, and the form of dog-tooth spar, and indicates how from either of these by cleavage the rhombohedral kernel of Fig. 20 can be obtained.

7. **Planes of Symmetry.**—There are many ways in which a figure may be symmetrical ; for example, by a spiral repetition of its parts, as in a circular staircase, or in the whorls of plants ; but crystalline symmetry is of a quite different character. We must, of course, in studying the symmetry of form, imagine our crystal to be geometrically perfect, and to have its similar faces equal in size. Such a crystal is, in the first place,

enclosed by plane faces; secondly, it may possess a centre of symmetry, or be "centro-symmetrical," so that any line drawn through the centre would meet the crystal in similar points at its two ends; thirdly, it may be divisible into two equal halves by bisection along a plane through the centre. (Other possibilities are discussed below, pp. 39, 47.)

Such a plane of bisection has, corresponding to every point of the crystal, a similar point situated at the same distance upon its opposite side, and is called a "plane of symmetry." If one-half of the bisected figure be placed against a mirror, the missing half is restored by the reflection; a plane of symmetry then is one over which the features of a crystal are repeated as though by reflection, and bear the same relation to each other which an object bears to its reflected image.

A crystal which can be cut into two such equal halves in only one way has only one plane of symmetry, but many crystals have more than one such plane. The cube possesses the highest degree of symmetry possible among crystals, and has nine such planes; it may be bisected along each of the three planes (1, 2, 3) parallel to its faces, and also along each

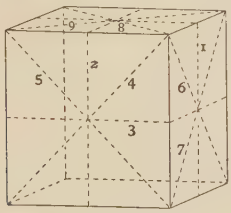


Fig. 22.—Symmetry-planes of Cube.

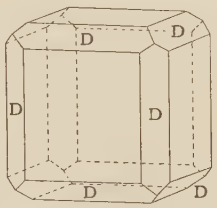


Fig. 23.—Combination: Cube and Dodecahedron.

of the six planes (4, 5, 6, 7, 8, 9), passing through a pair of opposite edges (Fig. 22, *cf.* also Fig. 70).

A natural crystal may have its faces of any size and various shapes, and may *appear* quite unsymmetrical, but the symmetry will be evident when it is converted in imagination into a geometrically perfect crystal. Choose any point as centre, replace each set of similar faces by planes parallel to them and equidistant from the centre; in this way a symmetrical figure will be constructed, in which the planes of symmetry of the crystal may easily be recognised; the dotted octahedron of Fig. 9 is derived thus from the misshapen figure. Crystallographic models are made after this fashion, and their planes of symmetry may easily be found by simple inspection. In this book the crystals are generally drawn not misshapen but in "equipoise," so that the similar faces are of the same size, in order that the symmetry may be more apparent.

8. **Forms.**—Any group of crystal faces obtained by modifying all the similar parts of a crystal in the same way is called a "form." These faces must also be similar to each other, and hence a form may equally well be defined as a complete group of similar faces upon any crystal.

Starting with the cube (which is one form), the eight faces obtained by evenly cutting away the corners constitute a form distinct from any

other such symmetrical group ; the octahedron is, then, one form derived from the cube.

Again, if one edge of the cube be replaced by a secondary face D equally inclined to the two cube-faces which meet in that edge, then every edge of the cube must be similarly replaced by virtue of its symmetry (Fig. 23). If the cube be cut away parallel to these planes until its faces have entirely disappeared, the resulting form is found to be the dodecahedron of Fig. 8. The dodecahedron, then, is a second form derivable from the cube, and Fig. 23 is a combination of the cube and the dodecahedron.

Every crystal is either a simple form or a combination of two or more forms.

9. **Derivation of Forms from the Cube.**—We may now discover all the forms which may belong to a mineral (for example, fluor-spar) by starting with a known crystal of the mineral (such as the cube) and replacing its edges and corners in imagination by a process akin to cleavage. This is the manner in which a wooden model of any form is most easily made : a primitive figure having been constructed in which all the similar faces are of the same shape and size, a new form is derived by modifying in the same way all the similar edges or corners. This may be done in the following three ways :

(1) *Truncation.*—When two similar faces meet in an edge, that edge may be replaced by a plane equally inclined to them (it must bear the same relation to the two faces, since they are similar, and therefore must make the same angle with each) ; or a corner in which three or more similar faces meet may be replaced by a plane equally inclined to them. The new face is then said to " truncate " the edge or corner.

(2) *Bevelment.*—When two similar faces meet in an edge, that edge may be replaced by a pair of planes *equally* inclined to the two faces respectively ; or a corner in which three or more similar faces meet may be replaced by a group of faces arranged in accordance with the symmetry. The new faces are then said to " bevel " the edge or corner.

(3) *Replacement.*—An edge or a corner between dissimilar faces may be replaced by a plane *unequally* inclined to them ; the new face is then said simply to " replace " the edge or corner.

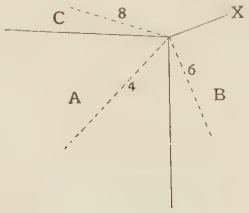


Fig. 24.

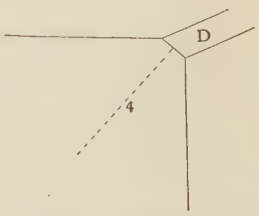


Fig. 25.—Truncation.

Thus if Fig. 24 represent one corner of the cube with its planes of symmetry, the edge X is truncated by D in Fig. 25 and bevelled by TT in Fig. 26. The corner is bevelled by three faces in Fig. 32 or by six faces in Fig. 35.

It will now be easy from these principles to construct all the possible forms of fluor-spar from the cube as primitive figure; they are found to be six in number, as follows:

(1) *Octahedron.* Fig. 7.—The form derived by truncating each cube-corner; this was found above to be the form resulting from the cleavage of fluor.

(2) *Dodecahedron.* Fig. 8. — The form derived by truncating the twelve edges of the cube (see Fig. 23 or 25); its faces are parallel to the six diagonal planes of symmetry. This figure is properly called the "rhombic dodecahedron" to distinguish it from the "regular dodecahedron of geometry," whose faces are regular pentagons, and which does not occur as a crystal form.

(3) *Four-faced Cube.* Fig. 27.—The form derived by bevelling each edge of the cube as in Fig. 26. The name indicates its resemblance to a cube with a low four-sided pyramid raised upon each cube-face; it is also

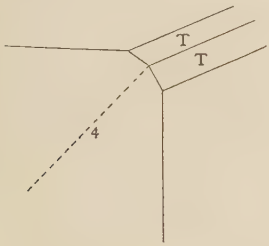


Fig. 26.—Bevelment.

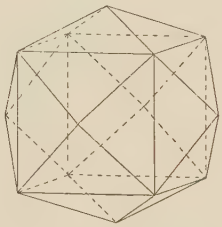


Fig. 27.—Four-faced Cube.

known as the tetrakis-hexahedron. The figure represents a crystal of fluor-spar from St. Agnes, Cornwall.

There are still three ways in which the corner of Fig. 24 may be modified. The octahedron-face is perpendicular to three of the symmetry-planes, namely, 4, 6, 8 (Fig. 22); the dodecahedron-face D of Fig. 25 is perpendicular to the symmetry-planes 1 and 4; the two bevelling faces T of Fig. 26 are perpendicular to the symmetry-plane 1. Now a face can only be repeated over those symmetry-planes to which it is not perpendicular, since over a perpendicular symmetry-plane it will coincide with its own reflection; but with varying inclination of the secondary face the following three forms are possible:

(4) *Three-faced Octahedron.* Fig. 30.—If the cube-corner be replaced by a face perpendicular to the symmetry-plane 8, so that it is inclined equally to the cube-faces A and B, but is more nearly perpendicular to the cube-face C (Fig. 28), the face must be repeated over the symmetry-planes 4 and 6, and will therefore be accompanied by two other faces, one perpendicular to 6, and one perpendicular to 4. Each cube-corner is thus replaced by a group of three faces, as in Fig. 29; the twenty-four faces thus obtained, when extended so as to obliterate the original cube, constitute the form of Fig. 30, called the three-faced (or triakis-) octahedron on account of its resemblance to an octahedron having a low three-sided

pyramid raised on each octahedron-face. The figure represents a rare variety of fluor-spar from Striegau in Silesia.

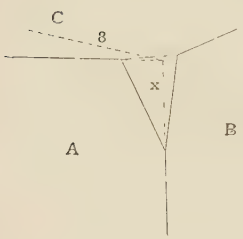


Fig. 28.

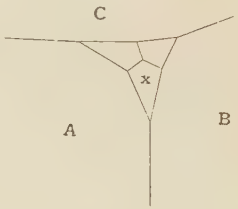


Fig. 29.

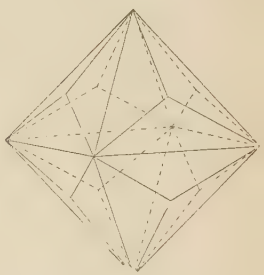


Fig. 30.
Three-faced Octahedron.

(5) *Icositetrahedron*. Fig. 33.- If the cube-corner be next replaced by a face perpendicular to the symmetry-plane 8, but one which is more nearly perpendicular to the cube-faces A and B than it is to C, as shown in Fig. 31, this face must be accompanied by two similar faces perpendicular to the symmetry-planes 4 and 6 respectively (Fig. 32); the modification of each cube-corner by a similar group of three faces will

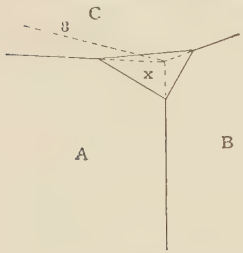


Fig. 31.

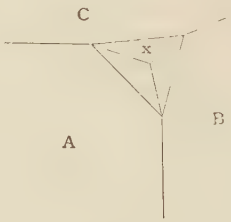


Fig. 32.

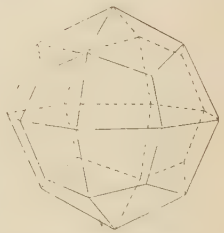


Fig. 33.—Icositetrahedron.

give rise to the form of Fig. 33, which is known as the 24-faced figure or icositetrahedron. The figure represents a crystal of analcite.

(6) *Six-faced Octahedron*. Fig. 36. — Finally, if the corner be replaced by a face x, Fig. 34, unequally inclined to the three cube-faces, and therefore not perpendicular to any of the three symmetry-planes 4, 6, 8, the face must be repeated over all these planes of symmetry and give six faces, as in Fig. 35. This group repeated over the three symmetry-planes 1, 2, 3, so as to be developed on all the remaining cube-corners, constitutes the form of Fig. 36, known as the six-faced (or hexakis-) octahedron on account of its resemblance to an octahedron having a low six-sided pyramid raised upon each of its faces. This figure represents a second rare variety of fluor-spar from Striegau.

The above are all the varieties of forms which can be symmetrically derived from the cube; any crystal of a mineral such as fluor-spar, which is known to occur in completely symmetrical cubes, must be either one of these simple forms, or a combination of two or more of them.

About the beginning of the last century the various forms derived from the primitive figures then known were very fully described by Romé de l'Isle and by Haüy. The cube and its six derived figures were known

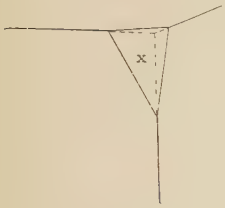


Fig. 34.

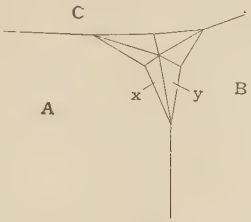


Fig. 35.

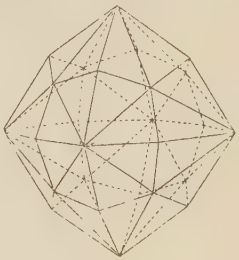


Fig. 36.
Six-faced Octahedron.

and classed together; other crystals were classified according to the primitive figure from which they could be derived.

10. **Crystal-axes.** — Haüy imagined crystals to be constructed of minute particles, having the form of the cleavage-figure, and suggested a mechanical explanation of the secondary faces; according to his view they could be regarded as due to the omission or suppression of a certain number of particles along certain directions.

Thus in galena the cleavage-kernel is a cube: a crystal of galena is therefore composed of minute cubic particles ranged side by side (Fig. 37). Suppose that during the growth of the crystal a certain number of these particles be omitted along the cube-edge A and the same

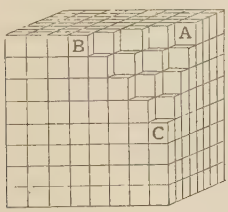


Fig. 37.

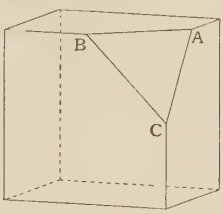


Fig. 38.

Haüy's representation of Secondary Faces.

number along the edges B, C, the result is a surface made up of the particles which lie in the plane ABC. Owing to the minute size of the particles this surface will appear smooth. We have only to suppose that the faces of a crystal are necessarily planes, and in this instance the surface is the octahedron-face (Fig. 38). Other faces can be derived in a similar manner by the omission of *unequal* numbers of particles along the edges; and the derivation of all secondary forms will then be equivalent to the cutting away, by new planes, of certain lengths measured on the edges of the primitive figures.

The manner in which a "dog-tooth" crystal of calcite can be built

up from the cleavage-rhombohedron is shown in Fig. 39, which is copied from Haüy's *Traité de Minéralogie*, published in 1801. Fig. 40 shows the appearance presented by the structure of Fig. 39 when the constituent particles become sufficiently small.

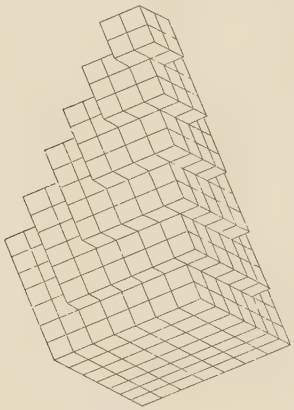


Fig. 39.

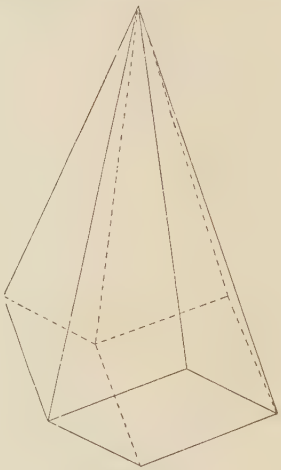


Fig. 40.

Now let OA, OB, OC (Fig. 41) be the three edges of a cube which meet in the corner O. If, according to the method of Haüy, a length OH be cut off by some face along the edge OA, then the same lengths must be cut off by the same or similar faces along the edges OB, OC, since these are similar to OA. The octahedron-face is obtained by taking three equal lengths along the three edges.

One plane of the three-faced octahedron of Fig. 30 is obtained by taking a certain length or intercept along the edge OC (see Fig. 28), and two intercepts less than this, but equal to one another, along the edges OA, OB; the remaining planes are derived by repeating the process beginning with each of the other two edges. One plane of the icositetrahedron of Fig. 33 is obtained by taking a certain intercept along one edge OC, and two intercepts greater than this, but equal to each other, along the edges OA, OB (Fig. 31). One plane of the six-faced octahedron of Fig. 36 is obtained by taking three unequal intercepts along the three edges. If, for example, the intercepts of the face x in Fig. 35 have the relative lengths $1 : 2 : 3$ along the edges taken in the order OA, OB, OC, then, since the three edges are similar, there must also be a face y making intercepts in the ratio $2 : 1 : 3$; the edges OB, OA being intersected by y at the same distances as OA, OB, respectively, by x. Treating all the three edges in this way we should

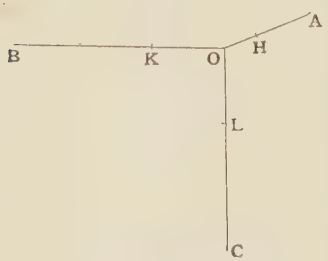


Fig. 41.

obtain the six faces shown in Fig. 35, and they are the same as those obtained above by repeating one face over the three planes of symmetry.

This method of treating the secondary faces has further the advantage of suggesting a notation by which the different faces may be distinguished, for the expression 3 : 2 : 1 might now be used to denote that particular face which has intercepts in the ratio 3 : 2 : 1, upon the three edges taken in the order OA, OB, OC.

In geometry the position of a plane in space is completely defined by means of the intercepts which it cuts off on three known fixed lines, meeting in a point.

Since in a crystal only the *direction* of a plane is of importance, the actual magnitudes of the intercepts need not be known, for a decrease or increase of their lengths, so long as their *ratios* are kept the same, merely corresponds to a shifting of the plane towards or from the intersection of the three lines of reference. Thus the direction of any face associated with the cube may be completely defined by the ratios of its intercepts OH, OK, OL upon the edges of the cube. The expression 2 : 2 : 2 would represent an octahedron-face equally inclined to the cube-faces and parallel to 1 : 1 : 1, for a doubling of the intercepts merely corresponds to the cutting away of a larger portion of the corner by a face parallel to 1 : 1 : 1.

The complete six-faced octahedron is obtained by treating all the eight cube-corners in the same way as the one corner of Fig. 35. It will be necessary then, in order to denote any particular face, not only to state the ratios of its intercepts, but also to indicate the corner to which it belongs.

Since the cube-edges are parallel at all the corners, the process of derivation is simplified and made more symmetrical by transferring the three lines of reference from the corners to the centre of the cube, extending each line in both directions, and distinguishing its ends as positive and negative.

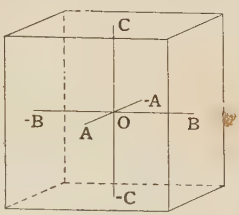


Fig. 42.

The three lines so placed are called the three "Axes" (see Fig. 42), and any particular face upon the crystal is denoted by the ratios of its intercepts upon the three axes, which are always taken in the same order, namely, OA, OB, OC.

Thus the octahedron-face upon the upper left-hand front corner of the cube might be denoted by 1 : −1 : 1, since a face parallel to it would pass through A, −B, C; an octahedron-face passing through −A, B, −C might be denoted by −1 : 1 : −1. The axes used here are the intersections of the three cube-planes of symmetry, and are more symmetrically placed in a cubic crystal than any other three lines of reference (such, for instance, as three edges of the octahedron); for this reason, as will be seen below (p. 28), the axes of crystals are always chosen from the intersections of their planes of symmetry where this is practicable.

When a face is parallel to one of the axes, as is, for instance, the dodecahedron-face D of Fig. 25, the corresponding intercept may be called infinity, and the face might then be denoted by the symbol ∞ : 1 : 1.

In the cube the three axes are said to be equal in length, since the intercepts made on them by an octahedron-face are equal. Many minerals, however, cannot be referred to three *equal* axes. The primitive form of anhydrite consists, like the cube, of three pairs of faces at right angles to each other, and the crystals show cleavage parallel to each pair of faces. Since, however, the cleavage parallel to the side faces is perfect, while the cleavage parallel to the front and back faces is less perfect, and that parallel to the top and bottom faces is still less so, these three pairs of planes cannot be similar. Hence, also, their edges are not in reality similar, but consist of three different sets which are to be distinguished from one another, and in a model or figure would be geometrically represented as of unequal length.

The three axes of the cube were found to be equal, because equal intercepts were made upon them by the octahedron-face; in the same way the relative lengths of the three axes of anhydrite must be found

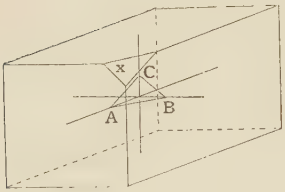


Fig. 43.

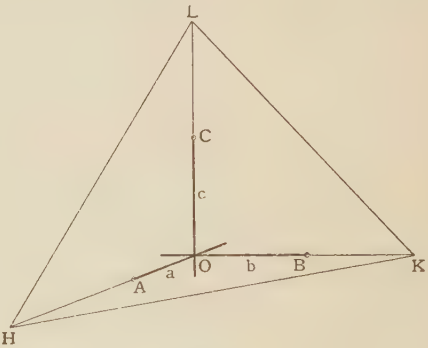


Fig. 44.

from the three intercepts made upon them by some secondary face which replaces the corner of the primitive figure. Crystals of anhydrite from Aussee in Styria are found to have their corners replaced by such faces (x, Fig. 43), but the intercepts which these faces make on the three edges are not equal. From the angles at which the face x is inclined to the faces of the primitive figure it is possible to calculate its intercepts on the axes; and it is found that in anhydrite the intercepts may be represented by the three numbers 893, 1000, 1001, taken in the order OA, OB, OC; so that they are not quite equal. The three axes to which crystals of anhydrite are referred are therefore taken in these proportions.

If now these three lengths be denoted by the letters a, b, c, any other face may have its direction and place on the crystal defined by the intercepts which it makes upon the axes, and may be denoted by a symbol $ma : nb : rc$, in which these three quantities give the ratios of its intercepts. Thus a face HKL (Fig. 44), which has intercepts in the ratios $OH : OK : OL = 3 \times OA : 2 \times OB : 2 \times OC = 3a : 2b : 2c$, may be denoted by the symbol $3a : 2b : 2c$. The use of axes was first introduced by C. S. Weiss of Berlin in 1818, and the above notation was employed by him.

The lengths of the axes are often called the "parameters," and the face used to determine these lengths is called the "parametral face."

In a cubic mineral the octahedron is the parametral form, and $a : b : c = 1:1:1$. In the case of anhydrite the face having the intercepts 893, 1000, 1001, has been chosen as parametral face, and $a : b : c = 893:1000:1001$.

11. **The Law of Rational Intercepts.**—According to Haüy's theory any face is a plane passing through a number of the small cleavage-particles of which the crystal is constructed.

Consider a mineral such as galena, whose cleavage is parallel to the cube-faces. A cube of galena is supposed to consist of minute cubes ranged side by side, as shown in Fig. 37. Consider a face replacing the cube-corner; it must pass through certain particles on the cube-edges; suppose it to pass through the eighth on OA, the sixth on OB, and the fourth on OC. The three intercepts will then be in the ratios of 4 : 3 : 2. (In Weiss's notation the face would be denoted by $4a : 3a : 2a$.)

If Haüy's theory of crystal structure be true it is clear that in galena, whatever the intercepts may be they must always be in the ratios of whole numbers, since they are obtained by removing a certain number of *cubic* particles along each edge.

In minerals such as anhydrite, in which the cleavage-particles are not cubic in shape, the intercepts must be in the ratios of multiples of the dimensions of a cleavage-particle, by which the parameters are determined.

From these considerations we are led to enunciate the "law of rational intercepts," according to which—

The intercepts made on the crystal-axes by any face of the crystal must be in the proportion of rational multiples of the parameters.

Haüy's own observations and those of subsequent workers have only tended to confirm the truth of this remarkable law, which is universally recognised at the present time as the geometrical basis of crystallography; and indeed without some such law the growth of crystals would present hopeless complexity, for there would be no limit to the number of forms possible.

Without necessarily accepting Haüy's theory of crystal structure we can adopt the law of rational intercepts as a statement of observed facts.

Expressed in Weiss's notation the symbol of any face being $ma : nb : rc$ (or, in cubic crystals, where the axes are equal, $ma : na : ra$), then according to the law of rational intercepts the numbers m, n, r, are not absolutely arbitrary, but must be whole numbers.

For instance, on p. 22 it was stated that in the three-faced octahedron of Figs. 30 and 46 the form is constructed by taking a certain intercept on one axis, and two equal but less intercepts on the other two axes; no limit was there placed upon the values of these intercepts; it might therefore be supposed that an infinite number of three-faced octahedra are possible, whose intercepts may have any ratios, such for instance as $\sqrt{2} : \sqrt{2} : 3$ or $\sqrt{3} : \sqrt{3} : 2$. But from the law of rational intercepts it now appears that these can only be whole numbers, such as 2 : 2 : 3 or 3 : 3 : 4.

Fortunately, moreover, it is found that the faces of common occurrence in Nature are only those whose intercepts are in the proportion of *very simple* multiples of the parameters, so that the numbers m, n, r, are almost always *simple whole numbers*, rarely greater than 5 or 6; this fact makes the study of crystals comparatively simple.

12. **Indices.**—The notation of Weiss has now been entirely superseded by a more convenient notation, which (though first employed by Whewell) is commonly known by the name of the Millerian system, in consequence of its use by W. H. Miller of Cambridge in his remarkable works on Crystallography and Mineralogy.

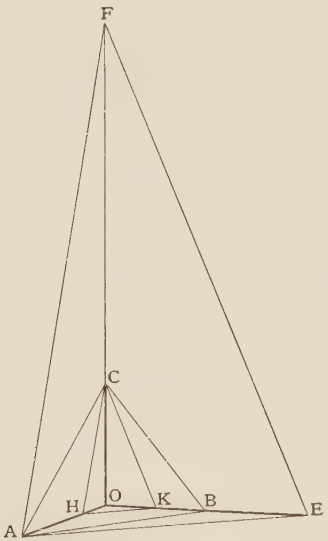


Fig. 45.

Let ABC in Fig. 45 represent the parametral face, whose intercepts are a, b, c, in a crystal of which OA, OB, OC, are the axes; then AEF will represent a second face, of which the intercepts are $OA = a$, $OE = 2 \times OB = 2b$, $OF = 4 \times OC = 4c$.

In the Millerian system we imagine this face shifted towards the centre O, without any change of its direction, until it occupies the position HKC, so that it no longer lies outside the extremities A, B, C, of the parameters. Its intercepts are now $OH = \frac{OA}{4}$, $OK = \frac{OB}{2}$, OC, *i.e.* $\frac{a}{4}, \frac{b}{2}, \frac{c}{1}$; the process has been equivalent to dividing the previous intercepts by 4.

The expression (421), consisting of the denominators of these fractional intercepts, is used in the Millerian notation as the "symbol" of the face, and the three numbers 4, 2, 1, are called its "indices."

In general, let the axes of a crystal be the three lengths a, b, c, then the symbol of any face is (hkl), where h, k, l, are three numbers such that the intercepts made by the face upon the axes are in the proportion of

$$\frac{a}{h} : \frac{b}{k} : \frac{c}{l}.$$

In a cubic crystal the octahedron is the parametral face, and the three axes are therefore equal and may be called a, a, a.

The intercepts of the octahedron are $\frac{a}{1}, \frac{a}{1}, \frac{a}{1}$, and its symbol is (111).

The intercepts of the dodecahedron-face D of Fig. 25 are ∞a, a, a, or $\frac{a}{0}, \frac{a}{1}, \frac{a}{1}$, and its symbol is (011).

The intercepts of the lowest face on the upper half of the three-faced

octahedron of Fig. 46 may be a, a, $2a$, or $\frac{a}{2}, \frac{a}{2}, \frac{a}{1}$, and the symbol of this face is then (221).

Intercepts measured in the negative directions are indicated by placing a negative sign over the corresponding indices.

Fig. 46 shows the indices of the faces in a complete three-faced octahedron.

When the axes are chosen symmetrically the faces which constitute a "form" generally have the same three numbers for their indices, and are only distinguished by the order and signs of these numbers: all the faces of Fig. 46, for instance, have symbols composed of the numbers 2, 2, 1.

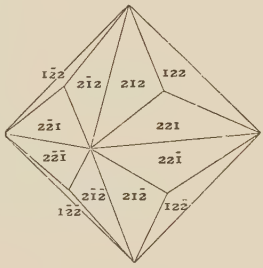


Fig. 46.—Form {221}.

The symbol of a form is denoted by enclosing the symbol of any one of its faces in a twisted bracket. Thus the symbol of the complete three-faced octahedron of Fig. 46 is {221}, this being understood to signify the whole group of faces, which must be developed together by virtue of the symmetry of the cube.

The axes of a crystal are not necessarily at right angles to each other; in order that the faces may have rational indices it is only necessary that the axes be chosen parallel to three edges of the crystal, and that their lengths be determined by the intercepts of a face.

Thus, if OA = a, OB = b, OC = c (Fig. 48) are the lengths of the axes

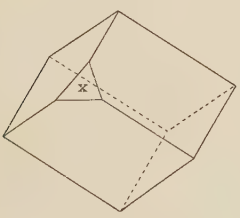


Fig. 47.

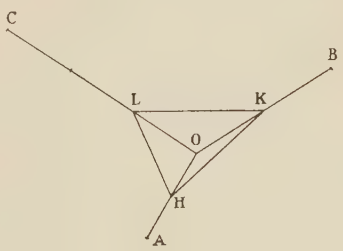


Fig. 48.

in the oblique-shaped crystal of Fig. 47, as determined by the intercepts made upon them by some face of the crystal (not shown) which has been selected as parametral plane, then any face x (or the plane HKL, which is parallel to it) has the symbol (hkl), where $OH : OK : OL = \frac{a}{h} : \frac{b}{k} : \frac{c}{l}$. In the figure, HKL is seen to have the symbol (223), since $OH = \frac{OA}{2}$, $OK = \frac{OB}{2}$, $OL = \frac{OC}{3}$.

The use of indices is at first somewhat confusing on account of their representing fractional values of the intercepts; it must always be borne in mind that the greater the index, the less is the corresponding intercept; in the face (321), for example, the intercept on the first axis is the least, and that on the third axis the greatest; the index 0 always indicates that the face is parallel to the corresponding axis.

13. **The Law of Rational Indices.**—In the Millerian notation the "law of rational intercepts" becomes the "law of rational indices." For if the intercepts of a face are ma, nb, rc, their values may be divided by the product mnr, and they become $\frac{a}{nr}, \frac{b}{rm}, \frac{c}{mn}$, so that the indices are nr, rm, mn. But m, n, and r are whole numbers, therefore these indices are also whole numbers. In its most general form the law may be thus stated (see Fig. 48):

Let OA, OB, OC, *be the three axes, chosen parallel to the edges formed by any three faces of a crystal which are not in one zone;*[1] *and let the lengths a, b, c, of the axes, as determined by the intercepts made upon them by a fourth (parametral) face of the crystal, be in the proportion*

$$a : b : c = \mathrm{OA} : \mathrm{OB} : \mathrm{OC}.$$

Then, if H, K, L, *are the points at which the axes are intersected by a plane parallel to any other face of the crystal,*

$$\mathrm{OH} : \mathrm{OK} : \mathrm{OL} = \frac{a}{h} : \frac{b}{k} : \frac{c}{l},$$

where h, k, l, must be whole numbers.

The ratios $a : b : c$ of the axes themselves (except in crystals derived from the cube) need not necessarily be (and are not in general) whole numbers.

It must be observed that the law of rational indices is true if *any* three edges[1] are chosen for axes; but, as was said above, it is always convenient to choose axes which are the intersections of planes of symmetry in order to simplify the indices.

14. **Zones.**—A number of faces may replace an *edge* of a crystal, as in Fig. 26, so as to intersect one another in parallel edges; if a line be drawn through the crystal parallel to that edge, and therefore also to the mutual intersections of the replacing faces, these faces are all of necessity parallel to that line. It is found that the faces of a crystal fall as a rule into sets which are parallel to a *few* such lines. Thus, for instance, the prism-faces of the quartz crystal in Fig. 2 are parallel to a vertical line and intersect in vertical edges. A set of faces on a crystal which are all parallel to the same line, and which would therefore, if they met, intersect in parallel edges, is called a "zone" of faces; the line to which they are parallel (which is supposed drawn through the intersection of the axes) is called the "zone-axis."

Zones are of great importance in the study of crystals, because it is found that all the faces on any one crystal, however complicated it may be, generally belong to a very few zones. But it rarely happens that all the faces which belong to a zone actually intersect each other in

[1] The three edges chosen as axes must obviously not be parallel edges; in other words, the three faces chosen to determine the axes must not belong to one zone (see Article 14).

parallel lines ; for the edges in which they would meet are often replaced by faces which do not belong to the zone.

15. **Projection.**—Before considering further the geometrical properties of crystals it will be necessary to describe a graphic method by which their symmetry and the arrangement of their faces may be very conveniently represented, a method first introduced into mineralogy by F. E. Neumann in 1823.

From what has been said above it is clear that the study of crystals is concerned, not with the shapes or sizes of the faces, but only with their directions ; now the perspective figures used above represent not only the directions but also the sizes and shapes of the faces ; the method next to be described indicates their directions alone.

The direction of a plane is completely defined if we know that of its normal. Let, then, any point O inside the crystal be chosen as " origin " ; let the whole set of faces be replaced by their normals, that is, by lines

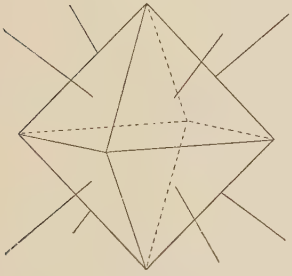


Fig. 49.—Normals of Octahedron.

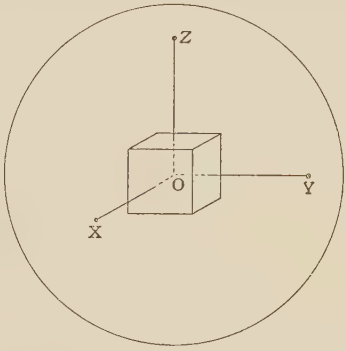


Fig. 50.—Axes intersecting sphere.

drawn perpendicular to them through the origin. Each normal now represents a face, and its direction may be defined by the angles which it makes with the three axes. If, for example, normals be drawn to the faces of the regular octahedron they constitute a sheaf of eight lines inclined to one another at angles of 70° 32′, and to the axes at 54° 44′ (Fig. 49). Such normals do not of course necessarily pass through their corresponding faces on an actual crystal ; a small facet is not always situated exactly upon its normal, but each face is regarded as a plane extended in all directions and the normal is drawn perpendicular to the plane.

Now it is possible to represent the normals themselves in a far more convenient way than by a perspective drawing. For this purpose the crystal is supposed to be surrounded by a hollow sphere having its centre at O (Fig. 50), and the normals are prolonged to meet the sphere in points ; in this way a point is found on the sphere corresponding to each face of the crystal, and is called the " pole " of the face. The axes of the crystal are also prolonged to meet the sphere in the points XYZ.[1]

[1] In the cube the axes coincide with the normals of the faces, since the edges are perpendicular to the faces, but in many crystals this is not so. (See pp. 35, 67, 83.)

If a series of faces belong to the same zone their normals must all lie in a single plane (called the "zone-plane"), which is perpendicular to the zone-axis; and since the zone-plane passes through the centre of the sphere it cuts the sphere in a "great circle," which is called the "zone-circle." Fig. 51 shows a crystal of quartz with its prism-zone A, B, C, and the corresponding zone-circle A′, B′, C′. If the planes of symmetry be also drawn through the centre they will intersect the sphere in great circles, which may be called "symmetry-circles."

In place, then, of the crystal we have a sphere bearing on its surface the three points (X, Y, Z) in which it meets the axes, and also a number of poles corresponding to the faces of the crystal; the poles of all the faces which belong to any one zone lie upon the corresponding zone-circle. The position of any pole may then be defined by its angular distances from the three points X, Y, Z, in other words by the arcs which join it to those

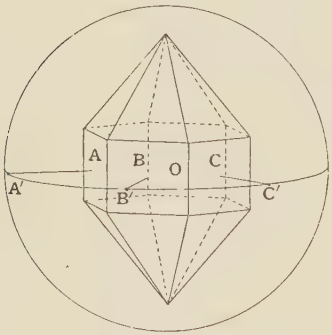


Fig. 51.—Zone-circle.

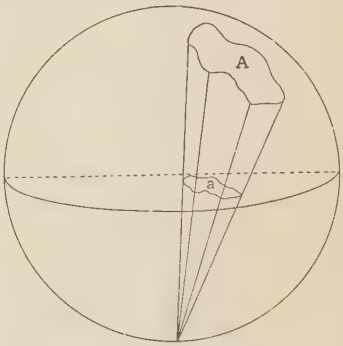


Fig. 52.—Stereographic Projection.

points; these measure, of course, the angles which the normal makes with the three axes.

If the sphere and the poles upon it were drawn in perspective, as in Fig. 51, there would not be much advantage in this method of representation as compared with the ordinary perspective figures (Figs. 5 to 50), but its value is immensely enhanced by the fact that there is a method of drawing the sphere (different from those usually adopted for maps of the globe) which is particularly convenient for the representation of crystal faces; this is known as the "Stereographic Projection."

In this method the plane of the equator on the sphere is taken as the plane of the paper on which the crystal is to be represented (called the "plane of projection"); crystal poles on the northern hemisphere are then joined to the south pole by straight lines passing through the paper, and the points in which these lines intersect the paper constitute a picture or "projection" of the poles on the northern hemisphere. Any figure drawn on the northern hemisphere may be projected in this manner, as shown in Fig. 52, where each point on the figure *a* is the projection of a corresponding point of the figure A drawn on the sphere. The whole figure *a* lies within the circle of the equator, which is often called the "primitive circle."

The peculiar advantage of this "stereographic" projection is that all circles on the sphere become either circles or straight lines in the plane figure, and not ellipses, so that they can be easily drawn with compasses and ruler.

The crystal is usually so placed within the sphere that its summit is towards the north pole, and the plane of the equator is placed in the

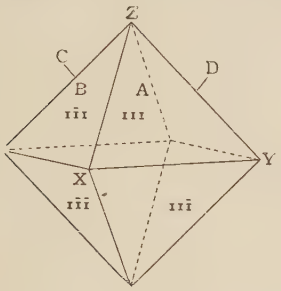


Fig. 53.—Octahedron in usual position.

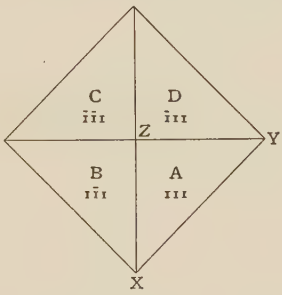


Fig. 54.—Octahedron viewed from above.

plane of the paper. Thus the octahedron of Fig. 53 is turned over into the position of Fig. 54, and the projection of its upper half then appears as in Fig. 55, in which the points ABCD represent the faces so lettered in Figs. 53 and 54, and the axes emerge at the points XYZ.

The projections of faces on the lower half of the crystal, whose poles lie on the southern hemisphere, will be found outside the circle of the equator, if they are projected from the south pole, as above. It is therefore convenient to project such by joining them to the *north* pole, and to represent them by circlets, as in Fig. 105. When the equatorial plane is a plane of symmetry these will exactly coincide with the poles belonging to the upper half of the crystal, since the northern and southern hemispheres are then similar (see Fig. 101).

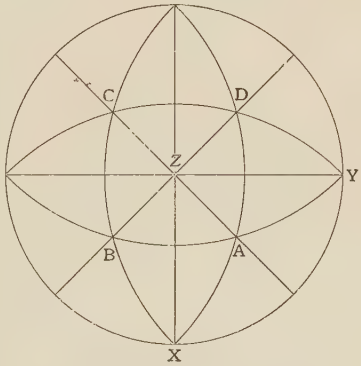


Fig. 55.—Projection of Octahedron.

Both zone-circles and symmetry-circles on the sphere become either circular arcs or straight lines (diameters) in the projection. The symmetry-circles of the octahedron (or cube) are shown in Fig. 55.

The following constructions will be found of use in drawing stereographic projections of crystals. Proofs of them will be found in text-books on crystallography.

Def.—The point on the sphere at 90° from the great circle representing any zone is called the "pole" of that zone.

I. *From a given pole* B, *in the projection, to set off a given arc along a given zone* ABC.

(*a*) If the zone ABC passes through the centre of the projection (Fig. 56), take P, the pole of the zone ABC. Draw PBD to meet the primitive circle in D. From D measure off the required arc DE along the primitive circle, and join EP, cutting ABC in F. Then BF is the projection of the arc required.

(*b*) If the zone ABC does not pass through the centre of the projection (Fig. 57), draw the diameter AC and the diameter GH perpendicular to AC and cutting the zone-circle ABC in K. Find P, the projection of the pole of the zone ABC; (this will lie on KH at a distance from K representing 90°). Draw PBD to meet the primitive circle in D, and proceed as above described.

The same constructions may obviously be used conversely, with Con-

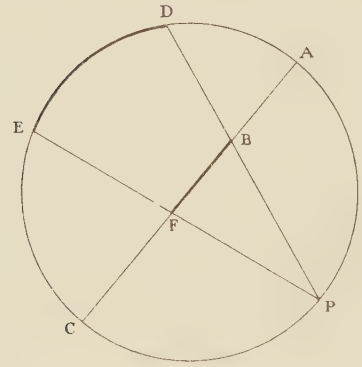


Fig. 56.

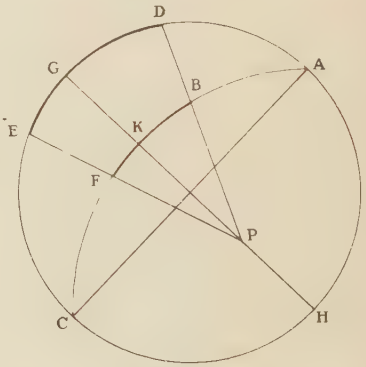


Fig. 57.

struction II, to determine the angle between two poles, whose positions in the projection are known.

II. *To draw the projection of the zone through two poles* A, B, *whose positions in the projection are known.*

If a straight line through A and B passes through the centre of the circle, this line will be the projection required. Otherwise the projection will be a circle, and it will be necessary to find a third point lying on it, *e.g.* the projection of the pole of the face parallel to A or B.

If one of the poles (say B) lies on the primitive circle, the pole of the parallel face will be B′, at the other end of the diameter through B, and the circle through BAB′ will be the projection required.

If neither pole is on the primitive circle, draw the diameter CBG (Fig. 58) through that pole (B) which is farthest from the centre, and in BG produced find the projection B′ of the pole at 180° from B, by Construction I (*a*), as shown (the angle DPE = 90°), and the circle through BAB′ will be the projection required.

III. *To measure the angle between two great circles, whose projections are given.*

Let the two great circles ABC, DBE intersect in B (Fig. 59). Along BC, BE set off the arcs BF, BG, each of 90°, and draw the great circle through FG. Since B is the pole of the great circle FG, the arc FG is equal to the angle between the great circles BF and BG.

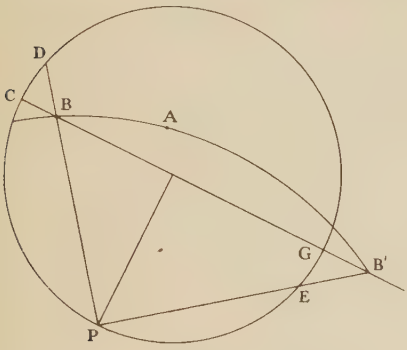


Fig. 58.

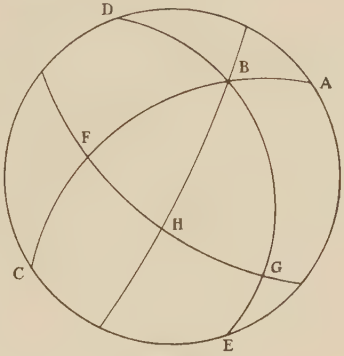


Fig. 59.

If it be desired to draw the great circle bisecting the angle between BF and BG (see p. 163), it is only necessary to bisect the arc FG in H (by I (*b*)), and draw the great circle through B and H.

16. **The Angle between Crystal Faces.**—The angle between two faces of a crystal is always measured by the angle between their normals. Thus the angle between the two faces A and B is the angle α which is enclosed between their normals (Fig. 60), and not β, which is the plane angle of a section through the faces perpendicular to their edge; the latter is what is commonly understood by the angle between two planes, except in crystallography, and was the angle used by crystallographers from the time of Steno until the introduction of the use of face-normals and their projections.

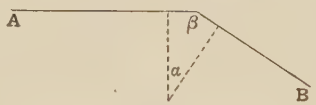


Fig. 60.

These two—α the normal-angle, and β the internal angle—are connected by the very simple relation $\alpha+\beta=180°$.

The use of the normal-angle in crystallography is very convenient for two reasons: it is the angle actually measured by the reflecting goniometer (see p. 113); and it is the arc-distance between the two poles on the sphere of projection.

Whenever the angle between two crystal faces (or "interfacial angle") is mentioned in this book it must be understood to mean the angle between their normals; thus the angle between two faces is very small when they nearly coincide, and is 180° when they are opposite to one another and parallel.

17. **The Use of Symbols.**—Since the indices of a given face determine its intercepts upon the three axes, and therefore implicitly also the inclinations of the face to the axes, there must be a simple relation connecting the indices with these inclinations. The relation is as follows:—

In the projection (Fig. 61) let P be the pole of a face whose indices are (*hkl*), and let XYZ be the points in which the axes meet the sphere, then

$$\frac{a}{h}\cos \mathrm{PX} = \frac{b}{k}\cos \mathrm{PY} = \frac{c}{l}\cos \mathrm{PZ}.$$

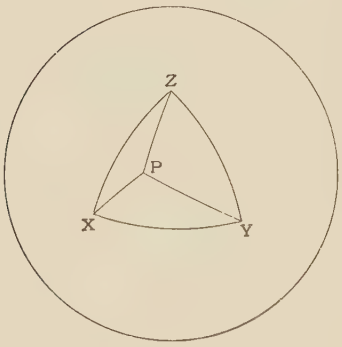


Fig. 61.

Here the arc PX measures the angle included between the axis OX and the normal to P; PY and PZ having similar significations.

These equations are the basis of all the relations which have been discovered between the angles and the indices of crystal faces; and the relations having once been established, all the problems of crystal calculation resolve themselves into simple problems of spherical trigonometry.

It will be sufficient here to indicate how the projection gives in a very simple manner not only the interfacial angles of a crystal but also the plane angles, and therefore the shapes, of its faces. If ABC (Fig. 63) be the poles of the three faces ABC (Fig. 62), then all their angular relations are given by the spherical triangle ABC, obtained by drawing great circles through AB, BC, CA. Thus its three sides AB, BC, CA, are equal to the

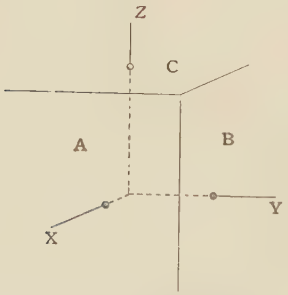


Fig. 62.—Axial Planes.

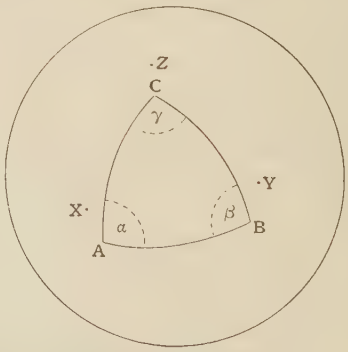


Fig. 63.—Projection of Axial Planes and Zones.

angles between the faces as measured with the goniometer. The angle α, at A, is the angle between the plane of the zone AC and the plane of the zone AB, *i.e.* the supplement of the angle between the edge AC and the edge AB; thus the three angles α, β, γ, are the supplements of the plane angles of the faces; and these plane angles may be deduced from the interfacial angles by means of the formulæ which connect the sides and angles of a spherical triangle.

If ABC are the three planes chosen for the primitive figure, whose intersections are taken as the axes, the angles α, β, γ are the supplements of the angles between the axes YZ, ZX, XY, respectively. The points X, Y, Z,

in which the axes meet the sphere, do not necessarily coincide with the poles of A, B, C. The axis X, being parallel to the faces B and C, must be perpendicular to their normals, and therefore X on the sphere is the pole of the zone-circle BC (see p. 31). Similarly Y is the pole of the circle CA, and Z is the pole of AB.

In some crystals, such as those derived from the cube, X, Y, Z do coincide with A, B, C; for in the cube the latter are at right angles, so that the axes are perpendicular to the faces.

In any case, if A, B, C are the "axial" planes, their symbols must be A = (100), B = (010), C = (001).

The following are a few of the more important applications of symbols.

18. **Zone-Symbol.** — Any two faces which are not parallel determine a zone by their intersection. Let their symbols be (hkl) and (pqr); then $[uvw]$ is called the "symbol of the zone," where

$$u = kr - lq\,; \quad v = lp - hr\,; \quad w = hq - kp.$$

The three numbers u, v, w are found by writing the symbols of the two faces one below the other, thus:

$$\begin{array}{cccccc} h & k & l & h & k & l \\ & \times & \times & \times & & \\ p & q & r & p & q & r \end{array}$$

and multiplying in the manner indicated by the cross-strokes, beginning with the second index; thus $u = (k \times r) - (l \times q)$, etc.

This process is called "cross-multiplication," and the symbol of a zone is said to be found by cross-multiplying the symbols of two faces belonging to it. The same symbol will be obtained for the zone whatever pair of faces be selected, provided that they are in that zone.

Example.—The symbol of the zone containing the two faces (111) and $(11\bar{1})$ is $[\bar{1}10]$, for:

$$\begin{array}{cccccc} 1 & 1 & 1 & 1 & 1 & 1 \\ & \times & \times & \times & & \\ 1 & 1 & \bar{1} & 1 & 1 & \bar{1} \end{array} = [(1 \times \bar{1}) - (1 \times 1),\ (1 \times 1) - (1 \times \bar{1}),\ (1 \times 1) - (1 \times 1)]$$

$$= [\bar{2}20] = [\bar{1}10].$$

The symbol of a zone is always enclosed in square brackets to distinguish it from the symbol of a face or of a form.

It is to be observed that the three numbers in a zone-symbol have not the same meaning as the three indices in a face-symbol and must not be confused with them.

They indicate the direction of the edge or zone-axis with reference to the axes of the crystal, in the following manner: Let OX, OY, OZ (Fig. 64) be the axes of the crystal and let the line OA be the axis of the zone. From any point P in OA, draw PQ parallel to OZ to meet the plane XOY in Q; similarly draw PR and PS parallel to OY and OX, respectively, and complete the parallelepiped OPQRSTUV. The inclination of OP to the axes is determined by the ratios OT : OU : OV, which may be written $ua : vb : wc$ where a, b, c are the parameters of the crystal. The numbers u, v, w then form the symbol of the zone.

Since only the direction of OP, and not its length, is of importance, a zone-symbol, like the symbol of a face, remains the symbol of the same zone when its component numbers are all multiplied or divided by any number, or when all their signs are changed.

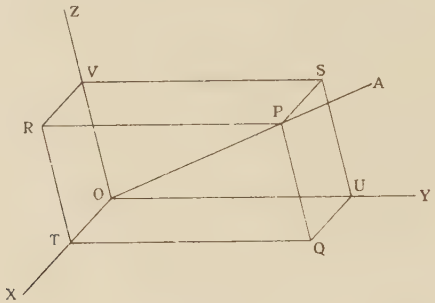


Fig. 64.

The chief uses of the zone-symbol result from the two following properties.

(1) If the face (hkl) belongs to the zone $[uvw]$, then

$$hu + kv + lw = 0.$$

Thus in Fig. 53 and the projection Fig. 55, the symbol of the zone containing the two faces (111) $(11\bar{1})$ is, as was shown above, $[\bar{1}10]$; should it then be required to know whether the face (110) belongs to this zone, the question is at once answered in the affirmative by applying the above test, for

$$(1 \times \bar{1}) + (1 \times 1) + (0 \times 0) = 0.$$

(2) If a face belongs to two zones its symbol is found by cross-multiplying the two zone-symbols in the manner described above.

Example.—A face which belongs to both the zones $[\bar{1}10]$ and [012] will have the symbol $(22\bar{1})$.

19. **The Zone-Law.** — The relation (2) of the last article suggests another way of expressing the law of rational indices. The zone-symbol got by cross-multiplying the rational indices of two faces must itself be rational; and the face-symbol got by cross-multiplying the rational symbols of any two zones must also be rational.

Hence if four faces of a crystal be chosen, as for determining axes, and, in a projection, if zone-circles be drawn through their poles in pairs, the intersections of these zone-circles will be the poles of faces having rational indices, and if other zone-circles be drawn through these, and the process repeated, all the poles so obtained will represent possible faces of the crystal, having rational indices; so that the faces obtained by constructing all possible zones on the crystal in this manner will be the same as those obtained by taking all possible sets of rational indices.

Thus, we may either say that all the faces of a crystal must have simple

rational indices when referred to axes determined by four of its faces, or that they must lie in simple zones constructed from those faces.

20. **Relations between the Symbols of Faces lying in a Zone.** — If the symbols of two faces be added together, index by index, the result is the symbol of a face replacing their edge, that is to say, of a face whose pole lies between their poles and on the same zone-circle. The same is true if any multiple of one symbol be added to any multiple of the other.

Example.—$2\times(12\bar{1})+3\times(2\bar{3}2)=(8\bar{5}4)$ is the symbol of a face lying in the zone between the faces $(12\bar{1})$ and $(2\bar{3}2)$.

This rule is of practical use in several ways, but especially in determining the sign to be given to the indices of a face which has been found by cross-multiplying two zone-symbols; thus the face belonging to the two zones $[\bar{1}10]$ and $[012]$ will be found to be either $(22\bar{1})$ or $(\bar{2}\bar{2}1)$, according as the first or the second zone-symbol is placed first in cross-multiplying. This is because any pair of zones must meet, not in one face alone but in two parallel faces, whose poles are the two points in which the two zone-circles intersect. But suppose that in this instance the face in question is known to lie between (110) and $(11\bar{1})$, then it must have the symbol $(22\bar{1})$.

The following relation between the angles and indices of faces lying in a zone is also of frequent use in determining the indices of a face from measurements made on the goniometer. If $P_1P_2P_3P_4$ (Fig. 65) are the poles of four faces lying in one zone, whose symbols are $(h_1k_1l_1)$, etc., then

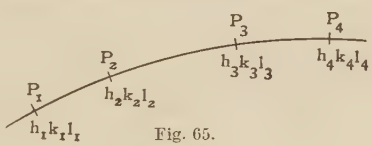


Fig. 65.

$$\begin{vmatrix} h_1k_1l_1 \\ h_2k_2l_2 \end{vmatrix} \cdot \begin{vmatrix} h_4k_4l_4 \\ h_3k_3l_3 \end{vmatrix} \Big/ \begin{vmatrix} h_1k_1l_1 \\ h_3k_3l_3 \end{vmatrix} \cdot \begin{vmatrix} h_4k_4l_4 \\ h_2k_2l_2 \end{vmatrix} = \frac{\sin P_1P_2}{\sin P_1P_3} \cdot \frac{\sin P_4P_3}{\sin P_4P_2},$$

where $\begin{vmatrix} h_1k_1l_1 \\ h_2k_2l_2 \end{vmatrix}$ represents the result of cross-multiplying any two pairs of these indices, *i.e.* $(h_1k_2-k_1h_2)$ or $(k_1l_2-l_1k_2)$ or $(l_1h_2-h_1l_2)$.

The expression $\frac{\sin P_1P_2}{\sin P_1P_3} \cdot \frac{\sin P_4P_3}{\sin P_4P_2}$ is called the "Anharmonic Ratio" of the four poles; and from the above relation it is possible to determine the indices of any face which lies in a zone with three known faces when the angles between the four faces have been measured.

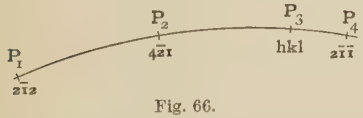


Fig. 66.

Example.—Find the indices of the face P_3, lying in the zone $P_1P_2P_3P_4$ (Fig. 66) in which the following angles and indices are known: P_1 $(2\bar{1}2)$, P_2 $(4\bar{2}1)$, P_4 $(2\bar{1}\bar{1})$; $P_1P_2=28°\ 54'$, $P_1P_3=54°\ 51'$, $P_4P_3=12°\ 1'$, $P_4P_2=37°\ 58'$.

We have $\begin{vmatrix} 2\bar{1}2 \\ 4\bar{2}1 \end{vmatrix} \cdot \begin{vmatrix} 2\bar{1}\bar{1} \\ hkl \end{vmatrix} = \frac{\sin 28° 54'}{\sin 54° 51'} \cdot \frac{\sin 12° 1'}{\sin 37° 58''}$

whence, cross-multiplying the first and last indices,

$$\begin{matrix} 2\times 4-2\times 1 & \bar{1}\times h-2\times l \\ 2\times h-2\times l & \bar{1}\times 4-2\times 1 \end{matrix} = \frac{1}{5} \quad \therefore \quad \begin{matrix} 6 & -h-2l \\ 2h-2l & -6 \end{matrix} = \frac{1}{5} \quad \therefore \quad h=-4l.$$

Similarly, cross-multiplying the second and third indices, we get $k=2l$. Hence (hkl) is $(\bar{4}21)$ or $(4\bar{2}\bar{1})$; and the position of the face in the zone shows that its symbol is in fact $(4\bar{2}\bar{1})$, since $(4\bar{2}1)+4\times(2\bar{1}\bar{1})=(12\,.\,\bar{6}\,.\,\bar{3})=3\times(4\bar{2}\bar{1})$.

21. **Calculation of the Axes.**—The axes of a crystal are easily deduced from a sufficient number of interfacial angles as measured with the goniometer, and in no case need this number exceed five. Thus, in the general case, let A, B, C (Fig. 67), be any three faces of a crystal which are chosen

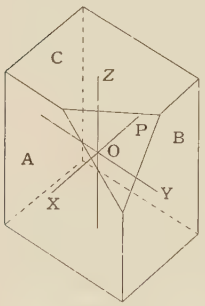


Fig. 67.

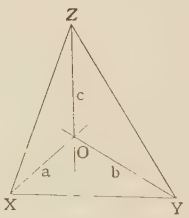


Fig. 68.

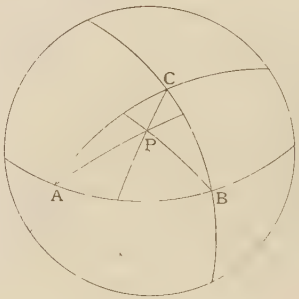


Fig. 69.

as axial planes, *i.e.* whose edges are taken to give the directions of the axes, and let P be the parametral face, *i.e.* the face which by its intersections with the axes is to determine their lengths. Let the plane XYZ of Fig. 68 be parallel to P. Then, from the plane triangle OYX,

$$\frac{a}{b}=\frac{\text{OX}}{\text{OY}}=\frac{\sin \text{OYX}}{\sin \text{OXY}}.$$

But OYX is the supplement of the angle between the edges AC and CP lying in the plane C, *i.e.* it is the angle between the zone-planes CA and CP; and OXY is the angle between the zone-planes CB and CP. Hence in the projection (Fig. 69)

$$\frac{a}{b}=\frac{\sin \text{PCA}}{\sin \text{PCB}}.$$

Similarly

$$\frac{b}{c}=\frac{\sin \text{PAB}}{\sin \text{PAC}}$$

and

$$\frac{c}{a}=\frac{\sin \text{PBC}}{\sin \text{PBA}}.$$

These angles can be calculated from five of the measured angles AB, BC, CA, and PA, PB, PC, by solving the triangles PAB, PBC, and PCA according to the rules of spherical trigonometry.

For example

$$\cos^2 \frac{\text{PCA}}{2} = \frac{\sin s . \sin (s - \text{PA})}{\sin \text{PC} . \sin \text{CA}},$$

where

$$s = \frac{\text{PA} + \text{AC} + \text{CP}}{2}.$$

The axial angles YOZ, ZOX, XOY, are the supplements of the angles CAB, ABC, BCA (p. 34), and can be found by solving the triangle.

22. **Axes of Symmetry. Centre of Symmetry. Alternating Symmetry.**— All the figures derived from the cube which have been considered above are symmetrical figures, and, like the cube itself, possess the nine planes of symmetry shown in Fig. 22. Now the symmetry of a figure consists in the repetition of its parts, but this repetition may take place in other ways besides reflection over a plane of symmetry. Consider the octahedron: each of its faces would be brought into the position of an adjoining face by rotating the octahedron through 90° about one of its diagonals, *e.g.* Z (Fig. 54); about any one of its three diagonals the faces of the octahedron are therefore symmetrically distributed, so that the crystal presents the same aspect after being rotated through 90°, 180°, 270°, or 360° about the diagonal.

Such a line is said to be an "axis of symmetry" to the figure, and since in this case faces are distributed in a fourfold manner about the axis, so that one quarter of a complete turn suffices to bring the crystal into a position in which its aspect is unchanged, the diagonal of the octahedron is said to be a "tetragonal axis."

It will be observed also that this line is one in which four planes of symmetry intersect. A tetragonal axis in which planes of symmetry intersect is distinguished as a "di-tetragonal axis."

Similarly it will be found that each of the four diagonals of a cube is a threefold or "trigonal axis" of symmetry both to the cube and to the six figures derived from it. Since three planes of symmetry intersect in this line it is called a "di-trigonal axis."

In addition to tetragonal and trigonal axes two other sorts of symmetry-axes, *viz.* "hexagonal" and "digonal" axes, are known.

A "hexagonal axis" is one of sixfold symmetry; the crystal presents the same aspect six times during a complete rotation about such an axis, at intervals of 60°. If the axis is the intersection of planes of symmetry it is said to be "di-hexagonal."

A "digonal axis" is one of twofold symmetry, about which a half-turn is required before the crystal presents the same aspect as it did before rotation. A "di-digonal axis" is the intersection of two symmetry-planes.

The manner in which one face can be derived from another belonging to the same form by rotation round an axis of symmetry is most easily grasped by noticing the repetition of one pole from another on the sphere

of projection. In the projection of Fig. 55 (*cf.* Fig. 101), the poles of the forms are grouped in a fourfold manner about the point Z where a di-tetragonal axis emerges, and in a threefold manner about the point A where a di-trigonal axis emerges.

Centre of Symmetry.—When each face is accompanied by a parallel face belonging to the same form, the one may be regarded as derived from the other by repetition about a centre; the crystal is then said to be "centro-symmetrical," since a line through the centre, perpendicular to any face, bears a second, similar face at its other end. In Figs. 53-55 the derivation of any face from the parallel face (*e.g.* of $\bar{1}\bar{1}\bar{1}$ from 111) may equally well be regarded as due to a rotation of 180° about an axis of even symmetry (such as Z), combined with reflection over the plane of symmetry to which that axis is perpendicular. Rotation through 180° about the symmetry-axis Z brings (111) into the position of ($\bar{1}\bar{1}1$), and reflection of the face over the plane perpendicular to Z brings it into coincidence with ($\bar{1}\bar{1}\bar{1}$). Some crystals, however, possess a centre without an axis or a plane of symmetry.

Axis of Alternating Symmetry.—In Fig. 20 every pair of adjacent faces at one end of the crystal may be regarded as derived from a similar pair at the other end by a rotation of 60° about the vertical axis followed by reflection over the horizontal plane, although the latter is not a plane of symmetry to the crystal. In such cases the axis is termed one of "alternating symmetry." In Fig. 20 it is di-hexagonal (*cf.* Fig. 176). In Figs. 191-193 it is hexagonal. In Figs. 130, 131, it is di-tetragonal.

23. **The Thirty-two Classes of Crystals.**—Some crystals possess only an axis of symmetry; some possess only a plane of symmetry; some are

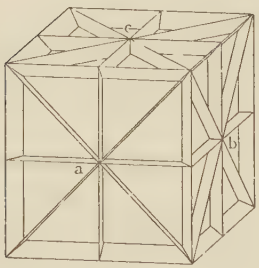


Fig. 70.—Symmetry-planes of Cube.

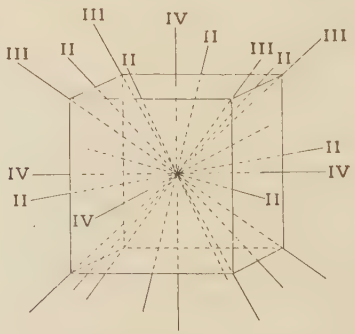


Fig. 71.—Symmetry-axes of Cube.

only centro-symmetrical, without planes or axes of symmetry; others possess more than one element of symmetry; while others again are entirely unsymmetrical. We may next, therefore, inquire in how many ways a crystal, that is to say a figure having plane faces which obey the law of rational indices (or the zone law), can be symmetrical; how its faces may be repeated about planes, axes, or a centre of symmetry either

singly or combined ; in other words, how many types of symmetry can exist among crystals. This problem has been solved.

In the first place it can be proved that an axis of symmetry is always parallel to a possible edge, and perpendicular to a possible face, of the crystal. Under these conditions it may be proved (by applying the law of rational indices) that axes of symmetry must be of either 2-, 3-, 4-, or 6-fold symmetry. Similarly, a plane of symmetry is always parallel to a possible face, and perpendicular to a possible edge of the crystal.

By combining the above elements of symmetry in all possible consistent ways it is then found that there can only be thirty-two distinct classes. A list of these is given on p. 91.

The most symmetrical of them is the complete cubic type which has been considered above. Here the crystal has not only the nine planes of symmetry shown in Fig. 70, but the thirteen axes of symmetry shown in Fig. 71. Each cube-axis (lettered IV) is an axis of di-tetragonal symmetry about which a rotation through 90° restores the original aspect of the crystal. Each cube-diagonal (lettered III) is an axis of di-trigonal symmetry about which a third of a complete turn is required ; and each line (II) joining the centres of opposite edges is an axis of di-digonal symmetry about which half a complete turn is needed to restore the aspect.

Now, since the thirty-two classes are obtained by combining in various ways the several elements of symmetry, it is not surprising that some of them are more closely allied to each other than to the remainder, and that they can be arranged into groups.

24. **The Six Systems.** — The thirty-two classes of crystals may be conveniently grouped into six systems, each characterised by the presence of certain elements of symmetry and referable to a distinct type of crystallographic axes. This arrangement is in harmony with a classification adopted on physical grounds (see p. 180) and represents a natural grouping of crystals.

One must always bear in mind the distinction between the crystallographic axes (to which the indices of the faces have reference) and the symmetry-axes. The latter do not necessarily coincide with crystallographic axes. In Fig. 71 the three tetragonal axes coincide with the crystallographic axes, but the remainder do not.

Now the three crystallographic axes must be either equal or unequal ; they must either be perpendicular or inclined to each other.

Since any three faces of the crystal which are not in one zone may be chosen as axial planes to determine the directions of the crystallographic axes, and any fourth plane which cuts them as parametral plane to determine their lengths, it is obvious that any crystal may, if desired, be referred to three *unequal inclined axes*. But *for convenience* the crystal-axes are always so selected as to be symmetrically placed within the crystal, and also if possible perpendicular to each other. For this purpose they must be so chosen that any plane of symmetry present is either perpendicular to a crystal-axis or equally inclined to two equal axes ; otherwise the axes are not symmetrical about it. Similarly, an axis of symmetry must either coincide with a crystal-axis, or (if an axis of two-

fold symmetry) bisect the angle between two equal crystal-axes, or (if an axis of three- or sixfold symmetry) be equally inclined to the three crystal-axes; otherwise the crystal-axes are not symmetrically repeated about it.

When an axis of symmetry is the only one of its sort in the crystal, it is called a "principal axis"; the vertical line of the figures in this book is a principal axis in the tetragonal and hexagonal systems.

The six systems and their characteristic symmetry are as follows (compare the figures on pp. 50 to 88):

(1) **Cubic System.**—Those crystals which have four axes of threefold symmetry, arranged parallel to the diagonals of the cube (which may be described as "Tesseral Symmetry"), are grouped together into the Cubic System (Fig. 72). Such crystals have also either three digonal or three tetragonal axes at right angles to one another, parallel to the cube edges. In virtue of this symmetry the crystals can always be referred to three equal crystallographic axes at right angles; since the digonal or tetragonal axes are parallel to possible edges, and may therefore be taken as crystal-axes, and the plane perpendicular to one of the trigonal axes (which is a possible face) will intercept these at equal distances.

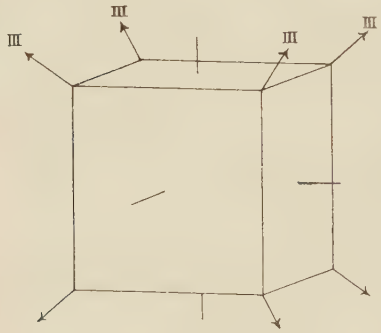


Fig. 72.—Tesseral Symmetry.

(2) **Tetragonal System.**—Crystals which possess a single axis of fourfold symmetry (but no trigonal axes) form the Tetragonal System. Such crystals will be referable to three axes at right angles, *viz.* two (*a*, *b*) of equal and one (*c*) of different length, the latter being parallel to the axis of fourfold symmetry (Fig. 73).

(3) **Hexagonal System.**—This system includes crystals which possess a single axis of sixfold, or one (but not more than one) of threefold symmetry. Three similar faces (such as R, Fig. 74, or three alternate faces of P, Fig. 75), equally inclined to the principal axis, and related to one another by one-third (or two-sixths) of a turn about this, are chosen as axial planes, while a face perpendicular to the axis is taken as the parametral plane. Thus the crystals are referable to three equal axes (*a*, *b*, *c*) inclined to one another at equal oblique angles.

(4) **Orthorhombic System.**—Crystals which possess three axes of twofold symmetry (Fig. 76) or at least one di-digonal axis (but no axes of higher symmetry) form the Orthorhombic System. Such crystals will have three possible faces at right angles and will therefore be referable to three rectangular axes (*a*, *b*, *c*), but no face will cut off equal intercepts on the axes, and the parameters are all unequal (Fig. 76).

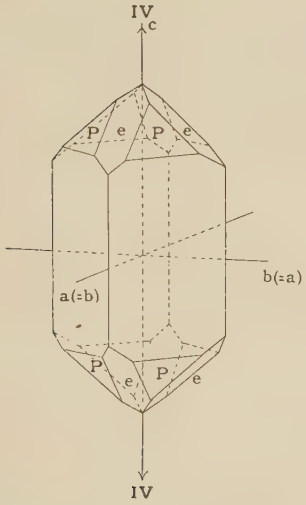


Fig. 73.—Tetragonal System, Rutile.

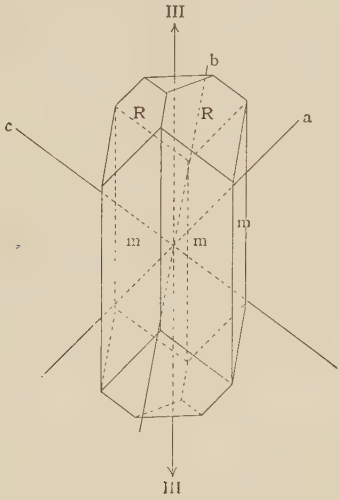


Fig. 74.—Hexagonal System.

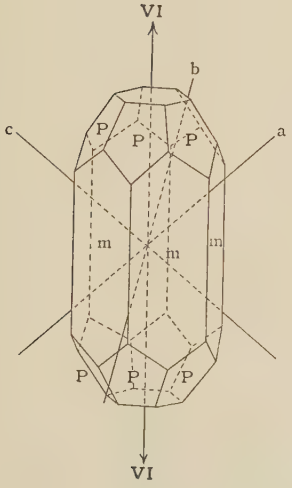


Fig. 75.—Hexagonal System.

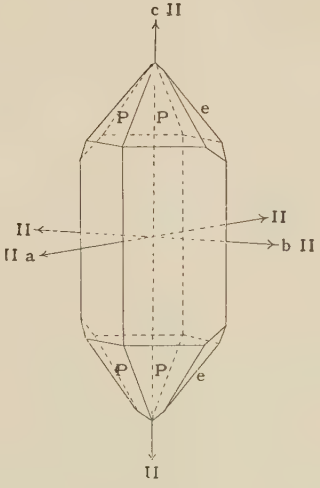


Fig. 76.—Orthorhombic System, Topaz.

(5) **Monoclinic System.**—Crystals which possess one axis of twofold symmetry and a plane of symmetry perpendicular to it (Fig. 77), or either of these elements alone, constitute the Monoclinic System. Such crystals are referable to a set of two axes (a, c) oblique to one another, with a third (b) perpendicular to both, no two of them being equal (Fig. 77).

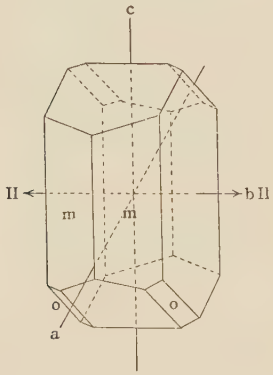


Fig. 77.—Monoclinic System, Orthoclase.

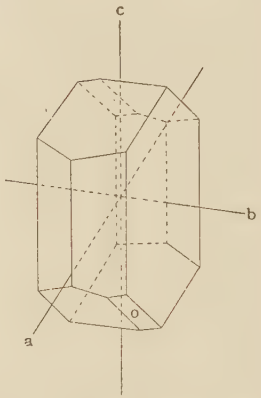


Fig. 78.—Anorthic System, Albite.

The edge taken to define the latter axis is parallel to the axis of twofold symmetry, or perpendicular to the plane of symmetry; the other two axes are parallel to edges lying in the plane of symmetry.

(6) **Anorthic System.**—Crystals which possess no axis or plane of symmetry form the Anorthic System. Such crystals have no faces at right angles and are referable only to three unequal oblique axes (Fig. 78).

25. **Relations between different Classes within a System.** The system to which a crystal belongs can usually be determined without difficulty by measurement of the angles on the goniometer, which enables the characteristic axes of symmetry to be recognised. It is not always possible to distinguish different classes belonging to the same system in this manner, for the following reasons: (1) some of the forms are common to two or more classes; and (2) some of the less symmetrical forms may, by combination with other forms having simple rational indices, present the appearance of a form belonging to a more symmetrical class in the same system. These points may be illustrated by boracite.

Boracite crystallises in the form of the tetrahedron (Fig. 79). It possesses four axes of threefold symmetry, each passing through one of the corners and the centre of the opposite face, and these are arranged in the same way as the diagonals of a cube. Boracite has, therefore, tesseral symmetry and belongs to the cubic system. It will be seen that in addition to the four trigonal axes boracite possesses the six planes of symmetry numbered 4, 5, 6, 7, 8, 9 in Fig. 22, but that its symmetry differs from the highest cubic type, mentioned on p. 17, in the absence of any planes of symmetry parallel to the cube-faces, and in the three axes parallel to the cube-edges being twofold and not fourfold.

If the tetrahedron of Fig. 79 be placed alongside a cube so that its tesseral axes are parallel to the cube-diagonals, it will be noticed that its faces occupy the positions of alternate faces of the octahedron, *viz.* the shaded faces of Fig. 80, and enclose the same angles, while the remaining octahedron-faces (unshaded in Fig. 80) form a similar tetrahedron, shown in Fig. 81.

Such forms as the two tetrahedra {111} and {1$\bar{1}$1}, which together

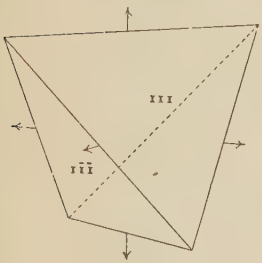


Fig. 79.

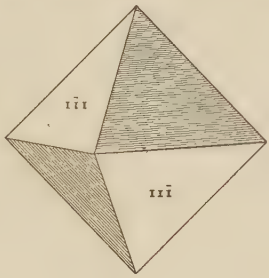


Fig. 80.

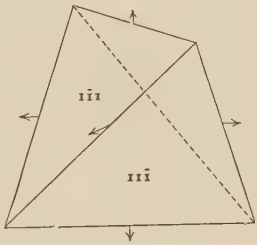


Fig. 81.

simulate a form belonging to a higher type of symmetry, are known as "supplementary" forms.

Boracite also crystallises in the combination of Fig. 82, when its edges are truncated by the six faces of the form {100}. When these faces are more largely developed, as in Fig. 83 (also a common habit of boracite), they are easily seen to be the cube-faces. Hence, whereas {111} in crystals of the boracite class is a tetrahedron instead of an octahedron, {100} is a cube just as in the "holosymmetric" class (see p. 46).

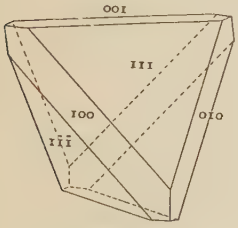


Fig. 82.

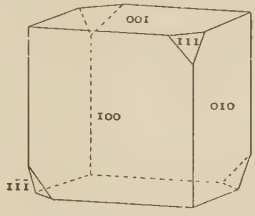


Fig. 83.

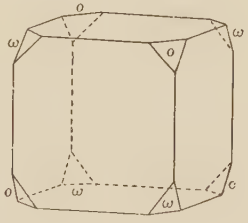


Fig. 84.

Figs. 82-84.—Boracite.

Again, boracite also crystallises in the combination of Fig. 84. This presents the appearance of the cubo-octahedron, a holosymmetric combination; it is really a combination of three forms, *viz.* the cube {100}, the tetrahedron *o* {111}, and the tetrahedron *ω* {1$\bar{1}$1}. Geometrically, the combination of two tetrahedra cannot be distinguished from an octahedron; but the true nature of such combinations is to be discovered from the physical characters of their faces. The natural crystal shows very clearly that *o* and *ω* belong to different forms, for the faces of *o* are bright and those of *ω* are dull.

The physical features of crystal faces not only serve to distinguish one form from another, but may also indicate the true symmetry of a single form. The fine lines or striations often found upon faces are especially useful for this purpose.

All minerals belonging to the cubic system may crystallise in cubes, but the cubes of two such minerals may really belong to different classes and differ in their symmetry.

Thus a cube of blende, striated as in Fig. 85, has six planes of

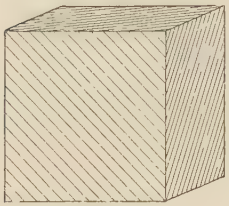


Fig. 85.

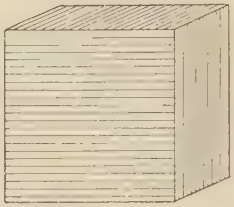


Fig. 86.

symmetry, namely those containing opposite edges, and belongs to the tetrahedral or boracite class just considered. But a cube of pyrites, striated as in Fig. 86, has only three planes of symmetry, namely those parallel to its faces, and belongs to a different cubic class.

In each system the class possessing the highest degree of symmetry is known as the " Holosymmetric " Class.

26. **Various Kinds of Forms.**—In a crystal having no symmetry all

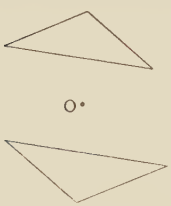


Fig. 87.—Pinakoid.

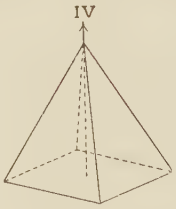


Fig. 88.—Tetragonal Pyramid.

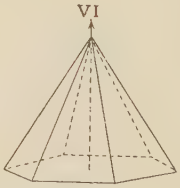


Fig. 89.—Hexagonal Pyramid.

the faces are unlike, and a form consists of a single *plane* only. Such a form is sometimes called a " pedion."

A form consisting of two similar parallel faces only is called a " pinakoid." Such a form may result from the repetition of a plane about a centre of symmetry (Fig. 87).

A set of three or more similar faces arranged round an axis of symmetry and meeting in an apex is called a " pyramid " (Figs. 88, 89, 90). If there is a plane of symmetry perpendicular to the axis the faces are repeated over it, and the form is a " bipyramid " (Figs. 91, 92). When a principal axis of symmetry is thus perpendicular to an (equatorial)

plane of symmetry, the crystal may be called "equatorial." In Figs. 88 to 90, the axis is "polar" or dissimilar at its two ends.

A form composed of three or more similar faces meeting in parallel edges is known as a "prism" (*e.g.* Fig. 93).

A pair of similar faces meeting in an edge and related about a plane of symmetry is called a "dome" (Fig. 94). If the faces are related about

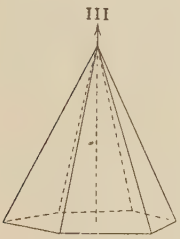


Fig. 90.—Di-trigonal Pyramid.

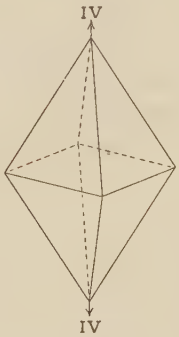


Fig. 91.—Tetragonal Bipyramid.

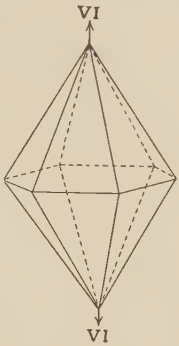


Fig. 92.—Hexagonal Bipyramid.

a twofold axis such a form is sometimes called a "sphenoid" (Fig. 95), and the double wedge-shaped figure obtained by the repetition of a face about three twofold axes at right angles is a "bisphenoid" (Fig. 100).

Repetition of a face about a threefold axis combined with a centre of symmetry gives rise to a "rhombohedron" (Fig. 96). If the axis is di-trigonal the resulting form is a "scalenohedron" (Fig. 97). These two

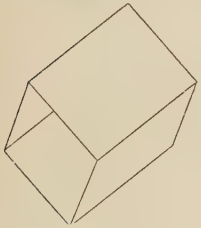


Fig. 93.—Prism.

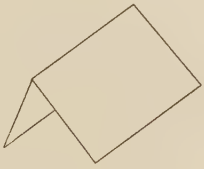


Fig. 94.—Dome.

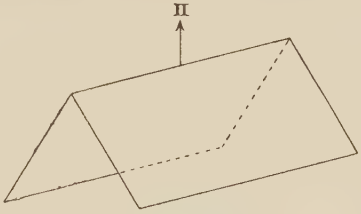


Fig. 95.—Sphenoid.

forms may also be described as due to repetition of a face about an axis of alternating hexagonal, or di-hexagonal, symmetry respectively.

An axis of alternating di-tetragonal symmetry gives rise to a "tetragonal scalenohedron" (Fig. 98).

A trigonal axis which is perpendicular to three digonal axes gives rise to a "trapezohedron" (Fig. 99). Trapezohedra also result from repetition about a tetragonal axis perpendicular to four, or about a hexagonal axis perpendicular to six digonal axes.

When an axis of n-fold symmetry is thus perpendicular to n digonal

axes, and there is no plane or centre of symmetry present, the crystal may be called "holoaxial," since it possesses all the symmetry-axes compatible with one another, and only axes (*e.g.* Figs. 99, 100).

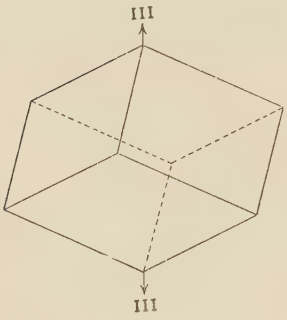


Fig. 96.—Rhombohedron.

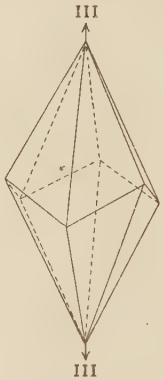


Fig. 97.—Hexagonal Scalenohedron.

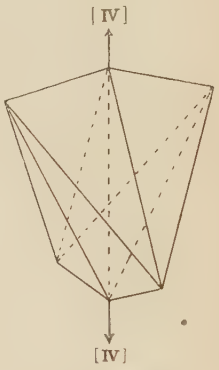


Fig. 98.—Tetragonal Scalenohedron.

The above forms are those obtained by the repetition of a face which is neither parallel nor perpendicular to an axis or plane of symmetry.

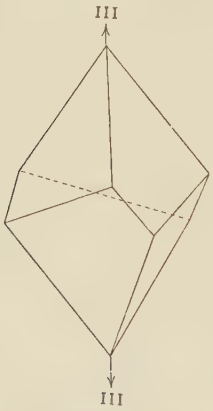


Fig. 99.—Trigonal Trapezohedron.

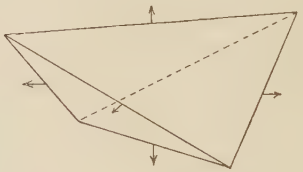


Fig. 100.—Bisphenoid.

We may now consider briefly twenty-two classes which are illustrated by the crystalline forms or combinations of well-known minerals and supply examples of central, equatorial, polar, alternating, and holoaxial symmetry.[1]

In any class, the various forms which may occur may be readily deduced from a consideration of a projection, by means of the "systematic triangle," as indicated in Article 27

[1] In the following figures of crystal forms axes of symmetry are terminated by arrow-heads. On the projections, circles which are dotted are not circles of symmetry.

The Cubic System

All crystals of this system possess four axes of threefold symmetry, and are referable to three equal rectangular crystal-axes.

27. **Cubic System — Holosymmetric Class — (Symmetry: Di-tesseral Central).** — All the holosymmetric forms have already been described, pp. 17 to 20; it only remains to indicate their positions on the projection. These are easily found by considering the circles of symmetry in Fig. 101.

The four di-trigonal axes emerge at O and corresponding points; repetition of a pole about them and about the centre of symmetry gives rise to the 47 other poles represented by dots and circlets on the projection. From the arrangement of these it may be seen that there are also present three di-tetragonal axes emerging at A and corresponding points; and six di-digonal axes emerging at D and corresponding points. The nine planes of symmetry have already been shown in Figs. 22 and 70.

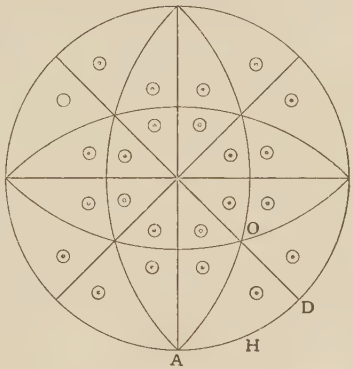


Fig. 101.—Cubic System, Holosymmetric Class. (Di-tesseral Central.)

In this class the sphere of projection is divided by the circles of symmetry into forty-eight equal and similar triangles, such as AOD, known as "systematic triangles," each of which has three unequal sides, namely the arcs AO, OD, DA. Now any pole on the sphere, whatever its position, must lie either at one of the corners of such a triangle, or on one of its sides, or within the triangle; the various possible forms of a holosymmetric cubic crystal may therefore be deduced by supposing a pole to occupy each one of these positions in succession, and by repeating it over the circles of symmetry. When the pole lies upon a circle of symmetry it cannot be repeated over the same, and it then represents a crystal face perpendicular to the corresponding plane of symmetry.[1]

(1) *Octahedron* {111}.—A pole situated at the corner O, if repeated over all the cube-planes of symmetry, gives rise to the octahedron (Fig. 7). Spinel and magnetite crystallise in perfect octahedra.

(2) *Cube* {100}.—If the pole migrate to the corner A, the form has six faces (Fig. 6). Well-formed simple cubes are found of galena, fluor, and salt.

(3) *Rhombic Dodecahedron* {110}.—If the pole migrate to the corner D, the form has twelve faces (Fig. 8); this, the dodecahedron, is the almost universal form of garnet, and is not infrequently found as a form of magnetite.

[1] A similar method may be used to determine the various forms which may occur in any of the other classes.

When the pole lies upon one of the sides of the triangle it belongs to one of the twenty-four-faced figures, since each side is common to two triangles; there are then three possible cases.

(4) *Three-faced Octahedron* $\{hhl\}$.—If the pole is situated between O and D the form is that of Fig. 30. A possible symbol for this figure is obtained by adding the indices of O and D, which gives $\{221\}$; the more general symbol is found by adding together any multiples of their indices. Thus $m\times(111)+n\times(110)=(m+n, m+n, m)$. The general symbol is therefore of the type $\{hhl\}$, where h is greater than l. A rare form of fluor-spar from Striegau in Silesia is the three-faced octahedron $\{441\}$.

(5) *Icositetrahedron* $\{hkk\}$.—When the pole lies between O and A the form is that of Fig. 33, and the indices are usually $\{211\}$. The general symbol of any icositetrahedron must be $\{hkk\}$, where h is greater than k;

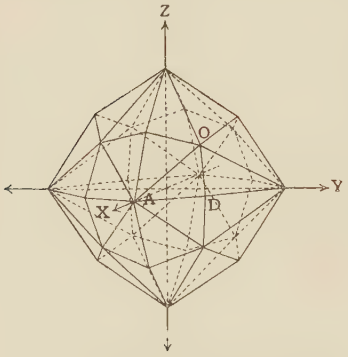


Fig. 102.—Holosymmetric Class: $\{hkl\}$, Six-faced Octahedron.

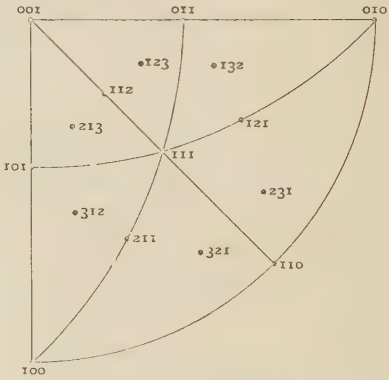


Fig. 103.—Poles in One Octant of Fig. 101.

since $m\times(111)+n\times(100)=(m+n, m, m)$. The icositetrahedron $\{211\}$ is a common form of analcite, leucite, and garnet.

(6) *Four-faced Cube* $\{hk0\}$.—When the pole lies between A and D, as at H, it belongs to a form $\{hk0\}$, of which the most common instance is $\{210\}$ (Fig. 27). $\{310\}$ is found as a simple form in fluor-spar.

(7) *Six-faced Octahedron* $\{hkl\}$.—When the pole lies within the triangle AOD, it must be repeated over all the planes of symmetry into every other such triangle, thus giving rise to forty-eight poles, which belong to the form of Fig. 102. Any face whose indices are all unequal belongs to this form, of which $\{321\}$ is a special and simple case.

The forty-eight-faced figure is scarcely known as a simple form, but some crystals of diamond present the appearance of a six-faced octahedron with curved faces (Fig. 476).

The poles of some of these forms, with their indices, are shown in Fig. 103, which represents one octant of Fig. 101.

The accompanying figure (Fig. 104) represents a crystal of spinel, from the Alban Mountains in Latium, which is extraordinarily rich in faces, being a combination of the forms: octahedron O $\{111\}$, dodecahe-

dron D {110}, cube A {100}, four-faced cube H {310}, two icositetrahedra I {311} and *i* {611}, and the six-faced octahedron S {531}.

This combination illustrates well the fact that in a complicated crystal all the faces constitute simple zones, and have simple rational indices. The edges of the octahedron are truncated by the faces of the dodecahedron; edges of {311} are truncated by faces of {310}; and edges of {310} by faces of {611}; while {531} replaces the edge of combination between {311} and {110}, as can be seen in each case from the parallel edges in the figure, or by addition of the indices.

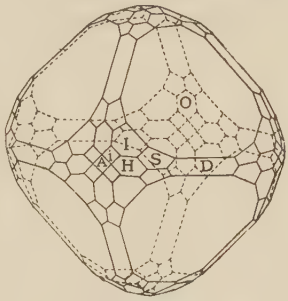


Fig. 104.—Spinel from Alban Mountains.

For examples of other holosymmetric combinations see the figures of fluor-spar (cubic habit), garnet (dodecahedral habit), galena (octahedral habit), in Part II.

28. **The Tetrahedrite Class — (Symmetry: Di-tesseral Polar).** — The crystals of this class possess four polar di-trigonal axes emerging at O and corresponding points, as shown by the projection (Fig. 105); these involve three di-digonal axes emerging at A and corresponding points; the six planes of symmetry are the planes passing through the cube edges of Fig. 22.

The faces obtained by repetition of (321) about these elements of

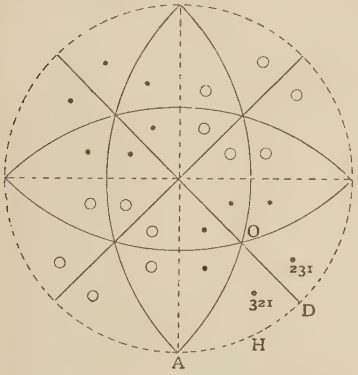


Fig. 105.—Tetrahedrite Class. (Di-tesseral Polar.)

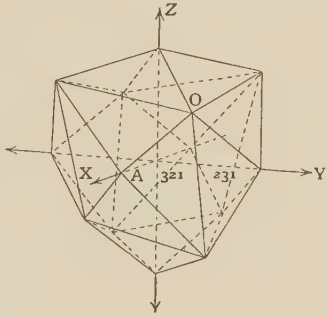


Fig. 106.—Tetrahedrite Class: {*hkl*}, Six-faced Tetrahedron.

symmetry constitute the *six-faced tetrahedron* {321} of Fig. 106, whose poles are shown in Fig. 105.

This figure is found, though rarely, as a simple form in diamond.

The other forms of this class are easily ascertained by imagining the pole (321) in Fig. 105 to migrate in succession to the various positions in the triangle AOD, and observing how the accompanying poles must then be distributed. Thus if (321) migrate to the corner A, the remaining

poles of the form must simultaneously migrate to the positions of the corresponding cube-poles, and *all* the six cube-faces will be represented. In this class {100} is consequently the *cube*, as in the holosymmetric class.

Similarly, on imagining the pole to migrate to D or H, the forms

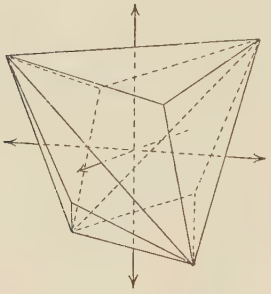


Fig. 107.—Tetrahedrite Class : {*hkk*}, Three-faced Tetrahedron.

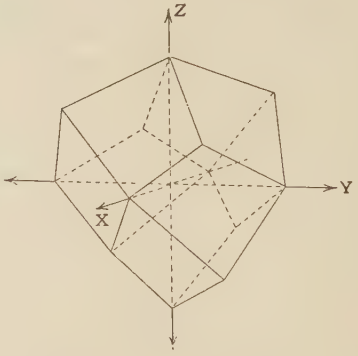


Fig. 108.—Tetrahedrite Class : Form {*hhl*}.

obtained are the *dodecahedron* and *four-faced cube* respectively. These forms cannot be distinguished from the corresponding holosymmetric forms unless they bear superficial markings or have physical characters which show that they lack planes of symmetry parallel to the faces of the cube

On the other hand, the remaining forms of this class are different

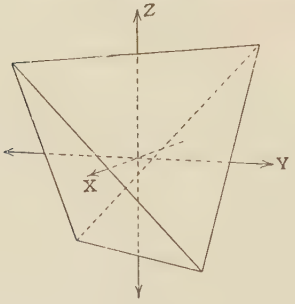


Fig. 109.—Tetrahedrite Class : {111}, Tetrahedron.

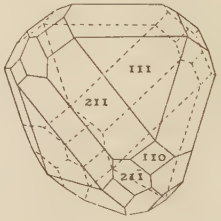


Fig. 110.—Tetrahedrite.

from those of the holosymmetric class. Thus, if $h > k > l$, {*hkk*} is the *three-faced tetrahedron* of Fig. 107, {*hhl*} is the form shown in Fig. 108, while {111} is the *tetrahedron* (Fig. 109). The tetrahedron is a common form of tetrahedrite or grey copper ore ; the other two forms are found in combinations. Fig. 110 represents a crystal of tetrahedrite from Dillenburg in Nassau, which is a combination of the forms : tetrahedron {111}, dodecahedron {110}, three-faced tetrahedron {211}, and the supplementary three-faced tetrahedron {21$\bar{1}$}.

For other tetrahedral combinations see the figures of tetrahedrite, blende, boracite, and diamond in Part II.

It will be seen that the cube-faces truncate the edges of the tetrahedron, and that the dodecahedron forms a three-faced pyramid on each corner of the tetrahedron, and has its edges truncated by the faces of {211} and {21$\bar{1}$}.

29. **The Pyrites Class — (Symmetry: Tesseral Central).** — The crystals

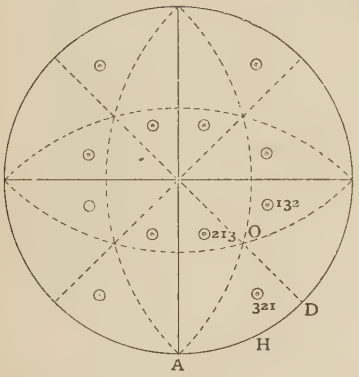


Fig. 111.—Pyrites Class. (Tesseral Central.)

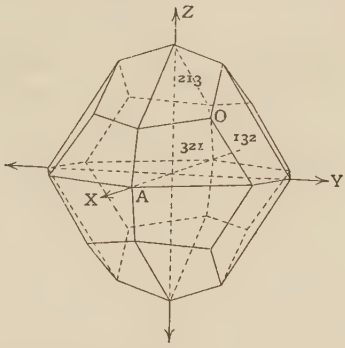


Fig. 112.—Pyrites Class: Form {*hkl*}.

of this class possess four trigonal axes emerging at O and corresponding points, and a centre of symmetry; these involve the three planes of symmetry of Fig. 111, and three di-digonal axes emerging at A and corresponding points. The faces which accompany (321) by repetition about these elements of symmetry constitute the form of Fig. 112, whose poles are shown in Fig. 111. Since the figure has centro-symmetry each face has another parallel to it, and no symmetry-axis is polar. Such a figure, with the indices {421} or {321}, is sometimes found as a simple form in iron-pyrites.

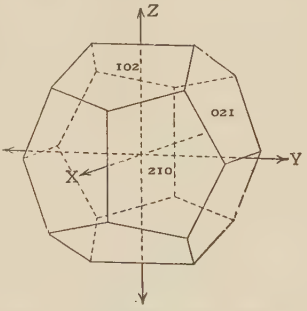


Fig. 113.—Pyrites Class: {*hk*0}, Pyritohedron.

Treating the other forms as before, it will be found that the *cube* {100}, *octahedron* {111}, *dodecahedron* {110}, *three-faced octahedron*, and *icositetrahedron* are identical with corresponding forms in the holosymmetric class. On the other hand, the form {*hk*0} (H in Fig. 111) has the shape shown in Fig. 113. This form is found in iron-pyrites, and is so characteristic of that mineral that it is often known as the "pyritohedron."

Fig. 114 represents a crystal of iron-pyrites from Elba, and is a combination of the forms: octahedron {111}, pyritohedron {210}, cube {100}.

30. **The Cuprite Class—(Symmetry : Tesseral Holoaxial).**—The crystals of this class possess four trigonal axes of symmetry and are holoaxial ; they have no plane of symmetry nor centre of symmetry, but they possess all the symmetry-axes possible, namely, tetragonal axes at A and corresponding points, trigonal axes at O, digonal axes at D. Repetition

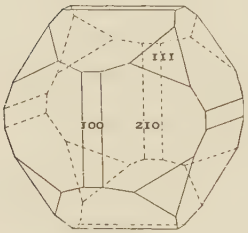


Fig. 114.—Pyrites from Elba.

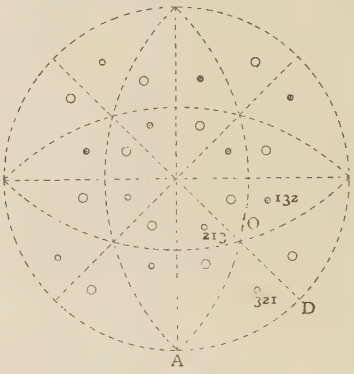


Fig. 115.—Cuprite Class.
(Tesseral Holoaxial.)

of the plane (321) about these axes gives rise to the form of Fig. 116, whose poles are shown in Fig. 115. This form consists of twenty-four similar irregular pentagons. Now if the form ¦312¦ be constructed (Fig. 117) it will be found that the two forms, though in a sense similar, are not identical. They will bear the same relation to one another which

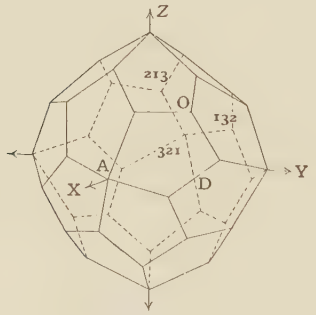


Fig. 116.—Cuprite Class :
Form $\{hkl\}$, $(h>k>l)$.

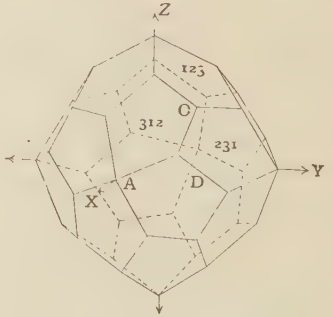


Fig. 117.—Cuprite Class : Form $\{hkl\}$, $(h>l>k)$.
(Enantiomorph of Fig. 116.)

a right hand bears to a left hand ; the one is the reflection of the other in a mirror. Two forms which are related to one another in this way and are not identical are said to be "enantiomorphous." All forms which have neither a centre nor a plane of symmetry are different from their mirror-images and exist in two enantiomorphous varieties. The forms belonging to the two preceding classes are not enantiomorphous

figures, because they possess planes of symmetry. The forms {321} and {312} are "supplementary," since they together make up the six-faced octahedron {321} of the holosymmetric class.

In the cuprite class it will be found that all the forms are the same as those in the holosymmetric class, with the exception of {*hkl*}, which is no longer a six-faced octahedron, but the form of Fig. 116 or 117. For this reason minerals belonging to this class will not betray their true symmetry unless they exhibit faces of such a form. Cuprite, although very rich in faces, usually presents only combinations of cube, octahedron, dodecahedron, and icositetrahedron, without faces of {*hkl*}. Fig. 118 represents a rare type of cuprite from Liskeard in Cornwall, a combination of cube {100}, octahedron {111}, and the form {968}.

Fig. 118.—Cuprite from Cornwall.

31. **The Ullmannite Class—(Symmetry: Tesseral Polar).**—The crystals of this class possess four polar trigonal axes, and consequently also three digonal axes. All the forms are the same as one or other of those in the preceding classes with the exception of {*hkl*}, one of the two enantio-

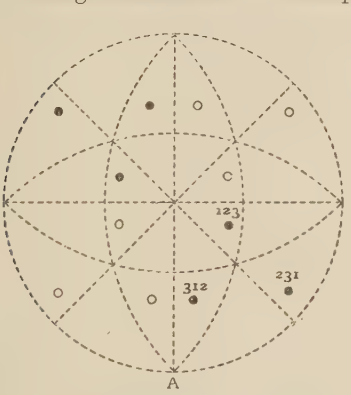


Fig. 119.—Ullmannite Class. (Tesseral Polar.)

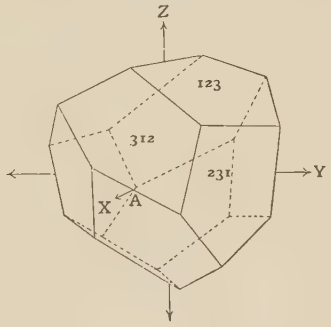


Fig. 120.—Ullmannite Class: Form {*hkl*} (*h*>*l*>*k*).

morphous varieties of which is shown in Fig. 120. The form {111} is a *tetrahedron* and {210} is a *pyritohedron*.

Crystals of ullmannite from Carinthia are tetrahedral in habit, those from Sardinia are pyritohedral, clearly indicating that the mineral cannot belong either to the pyrites class or to the tetrahedrite class, and that its symmetry must therefore be tesseral polar. Sodium chlorate also belongs to this class.[1]

[1] It is possible that iron-pyrites itself may eventually be proved also to belong to this class; as artificial crystals have been obtained which have an apparently tetrahedral habit.

The Tetragonal System

The crystals of this system possess one axis of fourfold symmetry, and are referable to three rectangular axes, two of which are equal.

32. **Tetragonal System—Holosymmetric Class—(Symmetry: Di-tetragonal Equatorial).**—The crystals of this class possess one di-tetragonal axis and an equatorial plane of symmetry. This involves also four di-digonal axes and a centre of symmetry. Two similar planes of symmetry S, at right angles to each other, are accompanied by a second pair Σ, and by the equatorial plane of symmetry R, as shown projected in Fig. 121. The di-tetragonal axis emerges at C, and the di-digonal axes at A, D, and corresponding points.

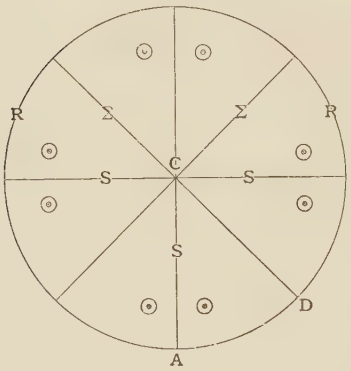


Fig. 121.—Tetragonal System, Holosymmetric Class. (Di-tetragonal Equatorial.)

The di-tetragonal axis C is chosen as the crystallographic axis Z, and two of the di-digonal axes (A) as the axes X and Y. The various forms may be ascertained, as in the cubic system, by considering the possible positions of a pole on the sphere with regard to the systematic triangle, ADC, formed by three circles of symmetry. The pole must fall either upon an angle, or upon a side, or within the triangle.

(1) *Tetragonal Prism* {110}.—A pole situated at D, when repeated over the S-planes of symmetry, gives rise to a form having four faces, which constitute a prism with a square base having the symbol {110} (Fig. 122).

The tetragonal prism {110} is not a closed figure and can only yield

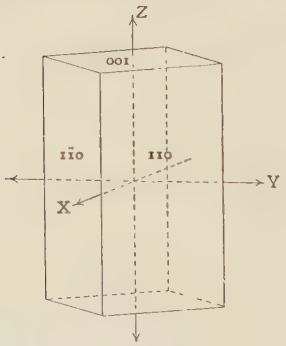


Fig. 122.—Tetragonal Prism: {110}.

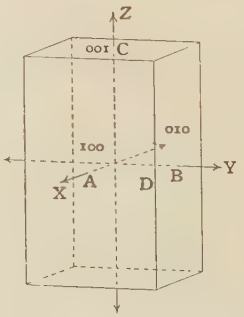


Fig. 123.—Tetragonal Prism: {100}.

one by combination with some other form; in Fig. 122 it is terminated by the faces (001) and (00$\bar{1}$), and the fact that these belong to a different form is here indicated by their smaller size.

(2) *Tetragonal Prism* {100}.—When the pole is situated at A the form is another tetragonal prism precisely similar in angles to the first. Geometrically speaking, Fig. 123 is merely Fig. 122 turned through 45°, but in a tetragonal crystal there will always be differences in the surface of the faces, or in other physical characters which serve to distinguish the one form from the other. This is also an open form. Its symbol is {100}. Since in passing from the cubic to the tetragonal system four of the dodecahedral planes of symmetry have disappeared, the faces (001) and (00$\bar{1}$) do not now belong to this form.

(3) *Basal Pinakoid* {001}.—When the pole is situated at C the form consists merely of the pinakoid or pair of parallel faces (001) and (00$\bar{1}$), which constitute the summit and base of Figs. 122, 123. In this or any of the following systems, a face which intersects the vertical axis, OZ, and is parallel to the two lateral axes, OX, OY, is called a "basal plane." Idocrase, from Wilui in Siberia, is found in square prisms terminated by the basal pinakoid.

(4) *Tetragonal Bipyramid* {*hhl*}.—When the pole is situated upon the

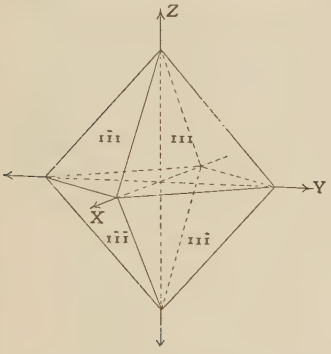


Fig. 124.—Tetragonal Bipyramid : {*hhl*}.

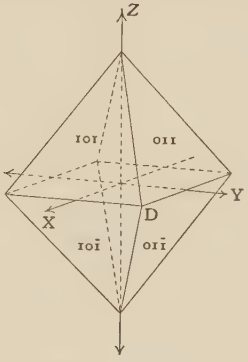


Fig. 125.—Tetragonal Bipyramid : {*h*0*l*}.

arc CD, the intercepts made by the corresponding face upon the two lateral axes are equal, and the first two indices in the symbol must also be equal; the form is therefore {*hhl*}, where *h* and *l* may have any rational values (Fig. 124). When the face belongs to the parametral form selected to determine the axial lengths its symbol is (111).

(5) *Tetragonal Bipyramid* {*h*0*l*}.—When the pole is situated on the arc CA it again belongs to a four-sided bipyramid {*h*0*l*}, in which *h* and *l* may have any rational values (Fig. 125). When the intercepts made by this form on the lateral and vertical axes are chosen to determine the axial lengths it is the parametral form {101}. This form, like the last, is a pyramid having a square base, but the two are not identical in angles, since {101} has the two equal axes parallel to the sides of its base, while {111} has the same axes for the *diagonals* of its base; consequently the two pyramids, if they have the same height, cannot have equal bases, and conversely, if they have the same base, one must be higher or lower than the other. Anatase is often found in simple bipyramids with a square base.

(6) *Di-tetragonal Prism* {*hk*0}.—When the pole falls upon the arc AD it must be repeated over both the S- and Σ-planes of symmetry and becomes an eight-faced prism (Fig. 126). This form, combined with the basal pinakoid, is found on crystals of idocrase.

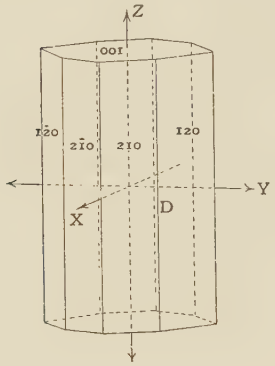


Fig. 126.—Di-tetragonal Prism : {*hk*0}.

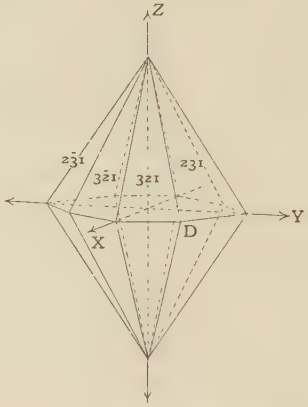


Fig. 127.—Di-tetragonal Bipyramid : {*hkl*}.

(7) *Di-tetragonal Bipyramid* {*hkl*}.—When the pole falls within the triangle ADC it must be repeated over all the planes of symmetry and gives rise to an eight-sided bipyramid (like Fig. 127), of which Fig. 121 is a projection. Such a form is only known in combination.

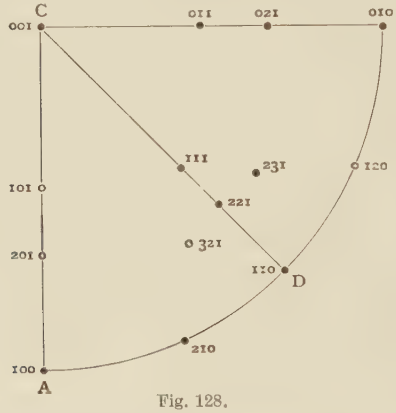


Fig. 128.

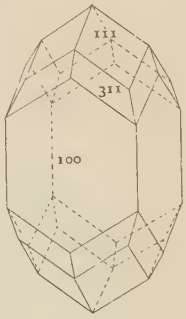


Fig. 129.—Zircon from Miask.

The positions of the poles of the preceding seven forms are shown in Fig. 128.

Fig. 129 shows a crystal of zircon from Miask, in the Urals, a combination of the forms {100} {111} {311}.

It will be observed that in a crystal belonging to the tetragonal system the direction of the vertical axis is fixed, since it coincides with the principal axis of symmetry. On the other hand, it is a matter of choice whether a given square prism is called {100} or {110}. Similarly the

crystal of Fig. 124 might either be called {111} or be turned through 45° and called {101}. Whichever position is adopted for one crystal is of course retained for all crystals of the same mineral.

33. **The Chalcopyrite Class—(Symmetry: Di-tetragonal Alternating).—**

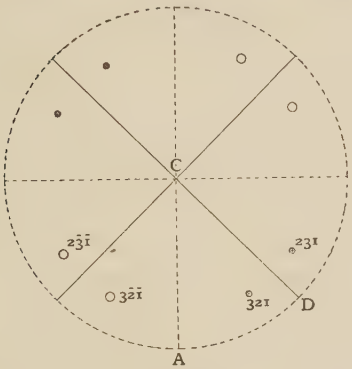


Fig. 130.—Chalcopyrite Class. (Di-tetragonal Alternating.)

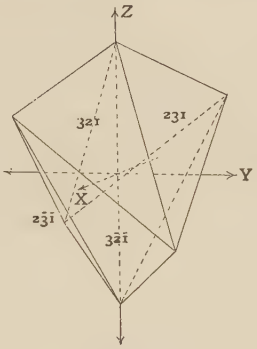


Fig. 131.—Chalcopyrite Class : {*hkl*}, Tetragonal Scalenohedron.

The crystals of this class possess two planes of symmetry at right angles to each other, intersecting in a di-tetragonal axis of alternating symmetry C, and combined with two digonal axes emerging at A and corresponding points in Fig. 130. There is no centre of symmetry. Repetition of the

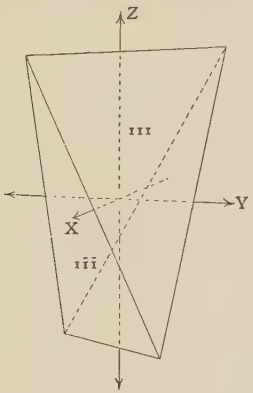


Fig. 132.—Chalcopyrite Class : {*hhl*}, Tetragonal Bisphenoid.

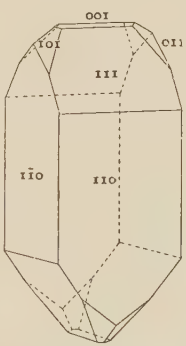


Fig. 133.—Chalcopyrite from Pennsylvania.

plane (321) about these elements of symmetry gives the *scalenohedron* of Fig. 131, whose poles are shown in Fig. 130.

The axis is not merely di-digonal, for each face of the scalenohedron can be derived from another face by a rotation of 90° about the vertical axis, combined with reflection over the equatorial plane, *e.g.* ($\bar{2}3\bar{1}$) from (321); rotation brings the latter to ($\bar{2}31$), and reflection gives ($\bar{2}3\bar{1}$). Such an axis is one of "alternating" symmetry.

The only forms of this class besides {*hkl*} which differ from the corresponding ones of the holosymmetric class are those whose poles lie upon a plane of symmetry (but not at C or D), *viz.* the *bisphenoids* {*hhl*} or {111}, (Fig. 132).

This class corresponds closely to the tetrahedrite class in the cubic system; thus the form {111} (Fig. 132) is very similar in appearance to the tetrahedron, but is in reality a *bisphenoid* or double wedge, whose faces are isosceles and not equilateral triangles, the vertical axis Z not being equal in length to the lateral axes X and Y. Fig. 133 represents a crystal of chalcopyrite from Pennsylvania, a combination of the forms: square prism {110}, bisphenoid {111}, bipyramid {101}, basal pinakoid {001}.

34. **The Scheelite Class — (Symmetry: Tetragonal Equatorial).** — The crystals of this class possess a tetragonal axis Z perpendicular to an equatorial plane of symmetry; they are therefore also centro-symmetrical. The face (*hkl*) repeated about these elements of symmetry gives rise to a *tetragonal bipyramid* (like Fig. 135), whose poles are shown in Fig. 134.

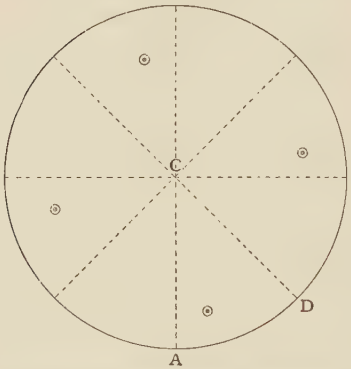


Fig. 134.—Scheelite Class. (Tetragonal Equatorial.)

The only other form which differs from the corresponding form in the holosymmetric class is the prism {*hk*0}, which is here not a di-tetragonal but a *tetragonal prism* (Fig. 136).

The crystallographic axes X and Y are not axes of symmetry in this class, neither do they in general emerge through the corners or edges of the forms. In this respect Figs. 135, 136 differ from Figs. 124, 122.

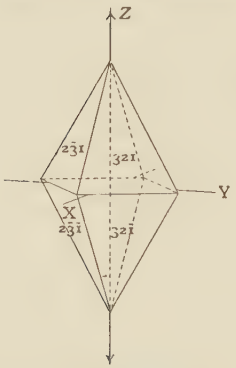


Fig. 135.—Scheelite Class: {*hkl*}, Tetragonal Bipyramid.

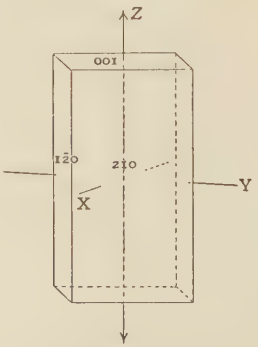


Fig. 136.—Scheelite Class: {*hk*0}, Tetragonal Prism.

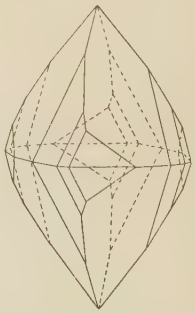


Fig. 137.—Scheelite.

Fig. 137 represents a crystal of scheelite from Zinnwald in Bohemia, a combination of four tetragonal bipyramids.

35. **The Wulfenite Class — (Symmetry: Tetragonal Polar).** — The crystals of this class possess only a polar tetragonal axis Z. Repetition of the face (*hkl*) about this axis gives rise to a *tetragonal pyramid* (like Fig. 139), whose poles are shown in Fig. 138. As in the last class, {*hk*0} is here also the *tetragonal prism* of Fig. 136. Further, since the tetragonal axis is polar, the form {001} is here not a pinakoid but a single *basal plane*.

Fig. 140 represents a crystal of wulfenite from Saxony, a combination of five tetragonal pyramids.[1]

36. **The Axial Ratio.**—In the cubic system the three axes were equal, but in a tetragonal crystal the vertical axis c is either greater or less than the two lateral axes a. When the axial ratio $c : a$ is known, the actual lengths of the intercepts made by any face are also known from its indices, and from these its inclination to the axes and to other faces may

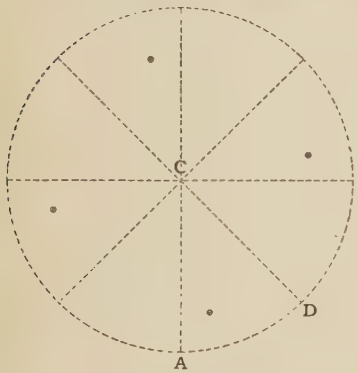


Fig. 138.—Wulfenite Class. (Tetragonal Polar.)

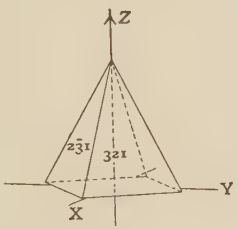


Fig. 139.—Wulfenite Class : {*hkl*}, Tetragonal Pyramid.

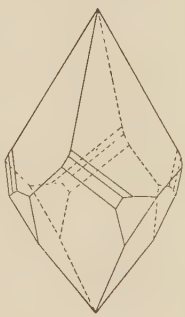


Fig. 140. Wulfenite.

be calculated. Conversely the axial ratio is found from the position of any face cutting the vertical axis and at least one lateral axis, by means of the equations on p. 34.

Thus in the crystal of cassiterite (Fig. 141), let e be chosen for (101), then

$$\frac{a}{1}\cos \mathrm{A}e = \frac{c}{1}\cos \mathrm{C}e,$$

and

$$\frac{c}{a} = \frac{\cos \mathrm{A}e}{\cos \mathrm{C}e} = \tan \mathrm{C}e\,;\ \text{since } \mathrm{AC} = 90°.$$

Or again, if p be chosen as (111), then

$$\frac{a}{1}\cos \mathrm{A}p = \frac{c}{1}\cos \mathrm{C}p,$$

therefore

$$\frac{c}{a} = \frac{\cos \mathrm{A}p}{\cos \mathrm{C}p} = \frac{\cos \mathrm{A}p}{\sin pm}\ ;\ \text{since } \mathrm{C}m = 90°.$$

[1] For the three remaining tetragonal classes (Di-tetragonal Polar, Tetragonal Holoaxial, and Tetragonal Alternating) see pp. 91, 93.

Now in the right-angled spherical triangle pmA (Fig. 142) (right angle at m),

$$\cos Ap = \cos pm \,.\, \cos Am = \cos pm \,.\, \cos 45°,$$

therefore

$$\frac{c}{a} = \frac{\cos 45°}{\tan pm}.$$

Hence the measurement of one suitable angle, for example Ae or mp,

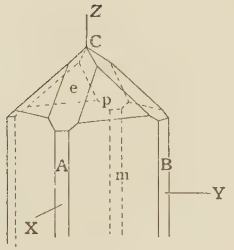


Fig. 141.

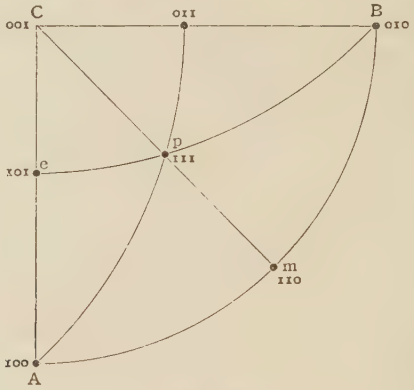


Fig. 142.

is enough to determine the axial ratio. If, however, the face does not lie in either of the zones CA or Cm, two angles will be needed to define the position of its pole in the triangle ABC, and enable its intercepts on the axes to be calculated. The axis a is usually taken as unity.

The Orthorhombic System

The crystals of this system possess an axis of twofold symmetry, which is either the intersection of two planes of symmetry or perpendicular to two other twofold axes, and are referable to three unequal rectangular axes.

37. **Orthorhombic System — Holosymmetric Class — (Symmetry: Di-digonal Equatorial).** — The crystals belonging to this class possess a di-digonal axis C and an equatorial plane of symmetry.

These elements involve two di-digonal axes, emerging at A and B, and lying in the equatorial plane, as shown projected in Fig. 143, and a centre of symmetry.

The three crystal-axes are, as in the cubic and tetragonal systems, the intersections of the planes of symmetry, but in this and the next succeeding class each of these lines is an axis of twofold symmetry and none can be called a principal axis as can the fourfold axis in the tetragonal system. Thus there is nothing to determine which of the three axes shall be chosen for the vertical, but after the vertical axis has been selected the crystal is by a general convention always so placed that of the two lateral axes the one (X) directed towards the observer is the shorter.

The three axes are then distinguished as the vertical axis (Z), the brachy-diagonal or short axis (X), and the macro-diagonal or long axis (Y), whose lengths are denoted respectively by *c*, *a*, *b*.

The various forms are then found as before :

(1) *Macro-pinakoid* {100}.—When the pole is situated at A the form consists of a pair of faces parallel both to the vertical axis and the macro-diagonal, and is therefore called the macro-pinakoid.

(2) *Brachy-pinakoid* {010}.—When the pole is at B the form consists of the pair of faces which are parallel both to the vertical axis and to the brachy-diagonal, and is called the brachy-pinakoid.

(3) *Basal Pinakoid* {001}.—When the pole is at C the form consists of a pair of faces parallel to the two lateral axes (X and Y).

Fig. 144 represents a combination of these three forms, constituting a rectangular-parallelepiped and resembling the combination of Fig. 123 in the tetragonal system, with the difference that in the orthorhombic

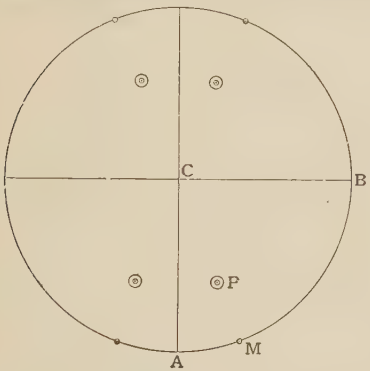


Fig. 143.—Orthorhombic System, Holosymmetric Class. (Di-digonal Equatorial.)

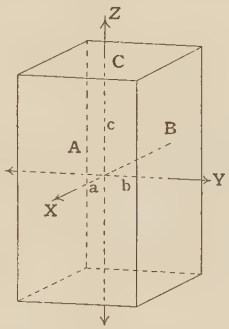


Fig. 144.—The Three Pinakoids.

crystal the three pairs of parallel faces belong to three different forms, and will therefore have different physical properties (*cf.* the cleavage of anhydrite, p. 24), and will be represented in a figure as of different sizes.

When the pole lies upon one of the sides of the spherical triangle ABC formed by the three planes of symmetry, it belongs to a form consisting of four planes, all parallel to one of the axes. Such a form is called a prism. It is, of course, an open form, and in a complete crystal can only exist in combination.

The next three forms are therefore :

(4) *Prism* {*hk*0}.—When the pole lies upon the arc AB (as at M), the form is a prism having four faces parallel to the vertical axis. The particular prism which passes through the extremities of the lateral axes, or which is selected to determine the lengths of those axes, has the symbol {110}, and is a prism with a rhombic base whose shorter diagonal is directed towards the observer ; in other words, the prism {110} is so placed that its obtuse angle is in front, and in the projection its poles

lie nearer A than B (as at M, Fig. 143). The prism is represented in Fig. 145, combined with the basal pinakoid.

(5) *Prism* {0*kl*}.—When the pole falls upon the side CB (as at L in Fig. 158), the form is an open prism similar in appearance to the last, but parallel to the brachy-diagonal. The particular prism whose faces

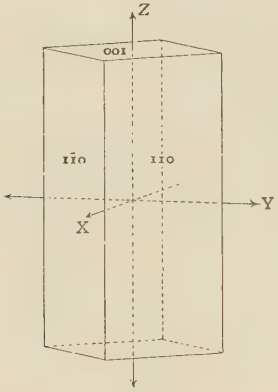


Fig. 145.—Rhombic Prism : {*hk*0}.

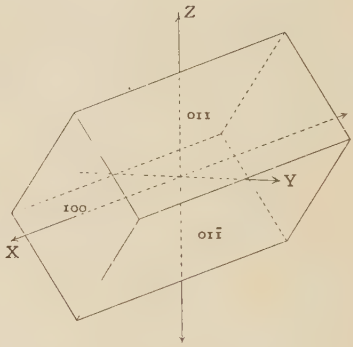


Fig. 146.—Rhombic Prism : {0*kl*}.

pass through the extremities of the axes has the symbol {011}. This form, closed by the macro-pinakoid, is represented in Fig. 146.

(6) *Prism* {*h*0*l*}.—When the pole is situated on AC (as at D in Fig. 158), the form consists of four faces parallel to the macro-diagonal ;

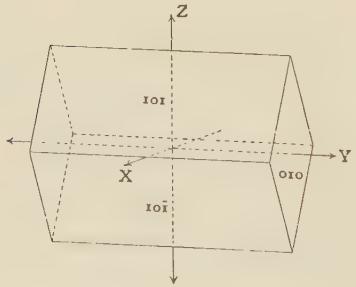


Fig. 147.—Rhombic Prism : {*h*0*l*}.

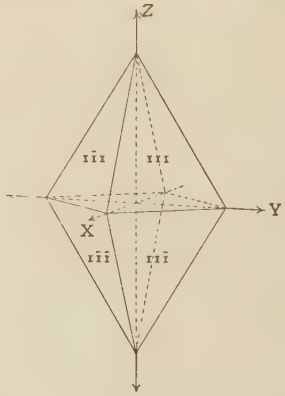


Fig. 148.—Rhombic Bipyramid : {*hkl*}.

and the particular prism whose faces pass through the extremities of the axes has the symbol {101}. This form, closed by the brachy-pinakoid, is represented in Fig. 147.

(7) *Bipyramid* {*hkl*}.—Finally, when the pole falls inside the triangle ABC (as at P), the form consists of eight faces which constitute a bi-pyramid with rhombic base (Fig. 148), shown in projection in Fig. 143.

Crystals bounded by the pinakoids alone (Fig. 144) are found in anhydrite ; prisms terminated by the basal or other pinakoids alone are found in barytes.

Simple rhombic bipyramids are found among the crystals of anglesite.

For holosymmetric combinations see Figs. 614, 722, 725.

38. **The Sulphur Class—(Symmetry : Digonal Holoaxial).**—The crystals of this class are holoaxial, since they possess three digonal axes coinciding

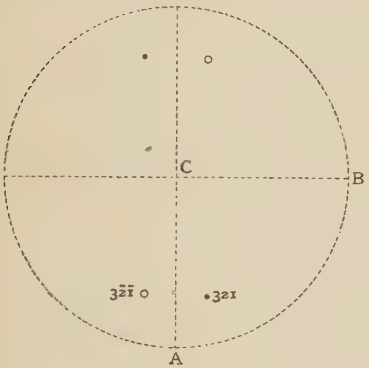


Fig. 149.—Sulphur Class. (Digonal Holoaxial.)

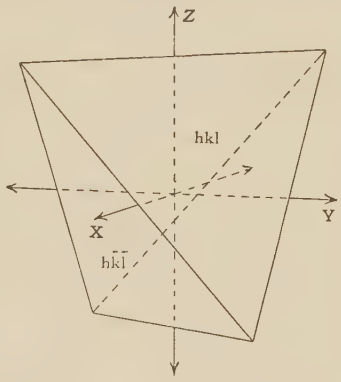


Fig. 150.—Sulphur Class : {*hkl*}, Bisphenoid.

with the crystal axes, and no other symmetry. They bear the same relation to those of the holosymmetric class that the tetrahedron bears to the octahedron. The face (321) (or any other pyramid face) repeated about these axes gives rise to a *bisphenoid* like Fig. 150, whose poles are shown in Fig. 149. All other forms are the same as in the holosymmetric class.

In crystals of sulphur from Sicily the absence of planes of symmetry is sometimes shown by a difference in the size of the faces of the forms {111} and {1$\bar{1}$1}, as in Fig. 151, which represents a combination of {111}, {1$\bar{1}$1}, {001}.

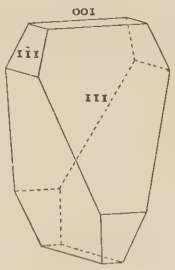


Fig. 151.—Sulphur.

39. **The Hemimorphite Class — (Symmetry : Di-digonal Polar).**—The crystals of this class possess a single polar di-digonal axis at C, in which two planes of symmetry intersect. This is a principal axis of the crystal and is chosen as the vertical axis Z. The face (321), repeated about this axis, and about the two planes of symmetry which intersect in it, gives rise to the *rhombic pyramid* of Fig. 153, whose poles are shown in Fig. 152.

The other forms in this class which differ from the holosymmetric forms are the *domes* {0*kl*} (Fig. 154), and {*h*0*l*} (Fig. 155), and the form {001}, which is here not a pinakoid but a single face (or *pedion*), the *basal plane*.

Hemimorphite from Aachen (Fig. 156) shows a combination of the macro-pinakoid {100}, the brachy-pinakoid {010}, the domes {101}, {301},

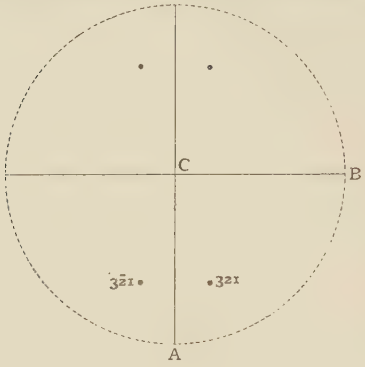


Fig. 152.—Hemimorphite Class. (Di-digonal Polar.)

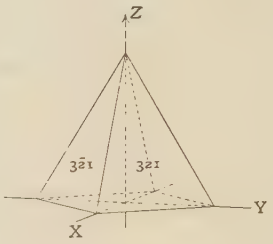


Fig. 153.—Hemimorphite Class : {*hkl*}, Rhombic Pyramid.

{011} and {031}, the prism {110}, the pyramid {12$\bar{1}$}, and the basal plane {001}. Crystals possessing a principal axis which is polar are sometimes

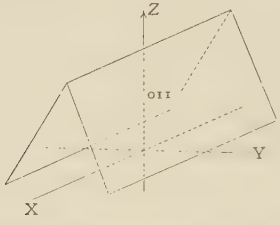


Fig. 154.—Hemimorphite Class : {0*kl*}.

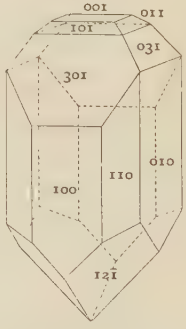


Fig. 156.—Hemimorphite.

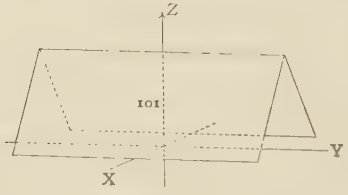


Fig. 155.—Hemimorphite Class : {*h*0*l*}.

called "hemimorphic," and the name of the mineral is derived from this peculiarity.

40. **The Axial Ratios.**—In the combination of Fig. 157 (which is to be compared with the projections Figs. 143 and 158), let M be taken as (110), P as (111), so that D is (101), L is (011). Then from the equations on p. 34, since AB = 90°,

$$\frac{a}{1}\cos \mathrm{AM} = \frac{b}{1}\cos \mathrm{BM} \quad \therefore \quad \frac{a}{b} = \frac{\cos \mathrm{BM}}{\cos \mathrm{AM}} = \tan \mathrm{AM}.$$

Similarly, $\frac{c}{b} = \tan \text{CL}$, and $\frac{c}{a} = \tan \text{CD}$.

The axis b is taken as unity.

Hence the axial ratios may be determined by the measurement of the angles of two prisms. If the faces which yield accurate measurements upon the crystal happen to be not those of a prism, but those of the

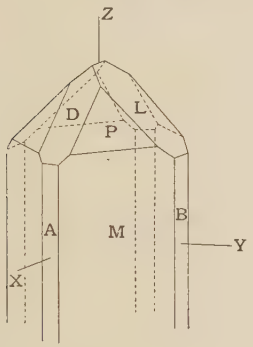


Fig. 157.

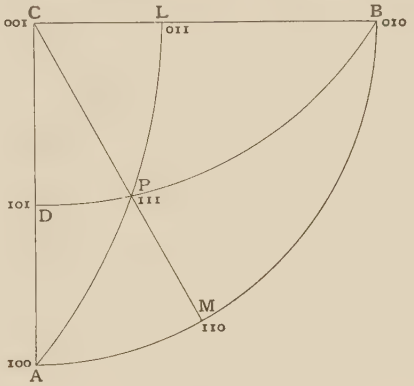


Fig. 158.

pyramid P, the formula becomes $a \cos \text{AP} = b \cos \text{BP} = c \cos \text{CP}$; since the axes X, Y, Z coincide with the normals of the faces A, B, C, and the points X, Y, Z on the projection coincide with the poles A, B, C.

The Hexagonal System

The crystals of this system possess one axis of threefold or one of sixfold symmetry, and are referable to three equal oblique axes.

41. **Hexagonal System. The two Sorts of Crystal-axes.**—In the preceding systems the crystal-axes have been three lines at right angles to each other. We now come to a system in which three equal axes, not at right angles, are symmetrically disposed about a principal axis of trigonal or hexagonal symmetry.

The arrangement of the axes in such crystals is best understood by comparing them with those of a cube so placed that one of its diagonals (an axis of di-trigonal symmetry) is vertical, as in Fig. 159.

The figure most nearly resembling this among the forms of the hexagonal system is the rhombohedron (Fig. 160). The crystal-axes being chosen parallel to its edges, the symbols of its faces, like those of the cube, are (100), (010), (001); but, of course, the angles of the rhombohedron are not right angles.

The planes of symmetry passing through the three edges which meet in the apex of the crystal are shown in the projection (Fig. 161); it will be noticed that the axes X, Y, Z do not here (as in the cubic system) coincide with the normals to (100), (010), (001).

The rhombohedron with three planes of symmetry is a form characteristic of a particular class belonging to the hexagonal system; but the holosymmetric class possesses six planes of symmetry intersecting in a di-

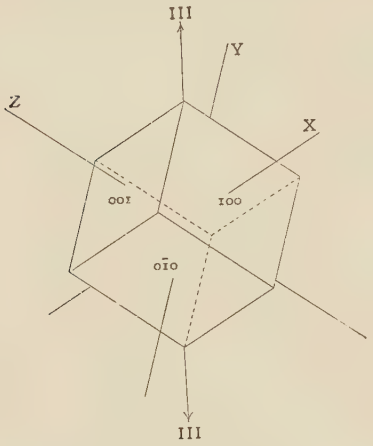


Fig. 159.—Crystal-axes of Cube.

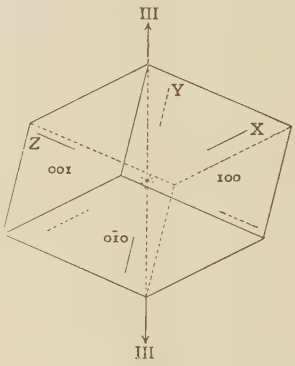


Fig. 160.—Crystal-axes of Rhombohedron.

hexagonal axis (Fig. 162). Now it was pointed out above (p. 45) that two different forms belonging to one class and having simple rational indices may, by their combination with each other, make up a form belonging to another class in the same system. Thus a combination of the two tetrahedra, {111} and {1$\bar{1}$1}, of Figs. 79, 81, is geometrically identical with the

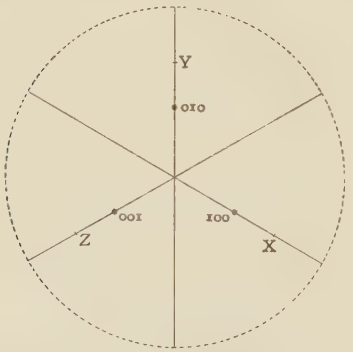


Fig. 161.—Symmetry-planes of Rhombohedron.

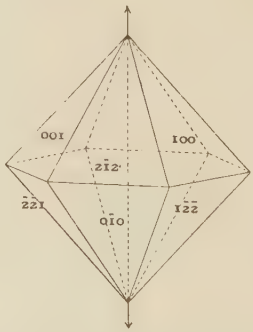


Fig. 162.—Hexagonal Bipyramid, composed of Direct and Inverse Rhombohedra.

octahedron of Fig. 80 (Article 25). Similarly, the hexagonal bipyramid of Fig. 162 is geometrically identical with a combination of the rhombohedron of Fig. 160 with that of Fig. 163, which (geometrically speaking) is simply the form {100} of Fig. 160 turned through 60° about the vertical axis. This rhombohedron possesses simple rational indices with

reference to the axes XYZ of Fig. 160; the front face, for example, intercepts these axes at distances $\frac{1}{2}$, $\bar{1}$, $\frac{1}{2}$ from the centre, and therefore has the symbol $(2\bar{1}2)$.

Two "rhombohedral" forms, such as $\{100\}$ and $\{2\bar{1}2\}$, which together make up a "hexagonal" form, are called a "direct" and an "inverse" form. Their indices (hkl) and (efg) are connected by the following relations:

$$e = 2(h+k+l) - 3h$$
$$f = 2(h+k+l) - 3k$$
$$g = 2(h+k+l) - 3l.$$

Thus if (hkl) be (010),

$$e = 2\times(0+1+0) - 0 = 2$$
$$f = 2\times(0+1+0) - 3 = \bar{1}$$
$$g = 2\times(0+1+0) - 0 = 2,$$

so that $(2\bar{1}2)$ is inverse to (010).

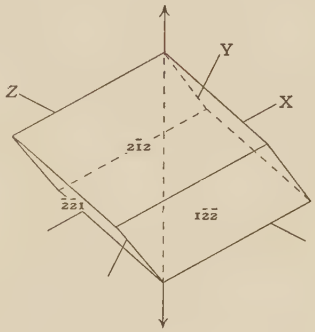


Fig. 163.—Inverse Rhombohedron.

It occasionally happens that the indices of the inverse form are composed of the same numbers as those of the direct; *e.g.* the face inverse to (321) is (369) or (123); but usually this is not so. Hence when the symmetry is hexagonal, so that the direct and the inverse faces belong to the same form, the crystal is usually referred to *four* axes, in order that all the faces of the form may be expressed by a single symbol.

If referred to the three crystal-axes XYZ, the hexagonal bipyramid would require a double symbol—six of its faces being denoted by $\{100\}$, the other six by $\{2\bar{1}2\}$, (Fig. 162). It is therefore referred to four "hexagonal axes" x, y, z, w, as in Fig. 164, instead of the "rhombohedral

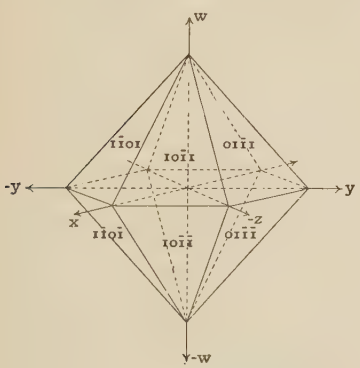


Fig. 164.—Hexagonal Bipyramid.

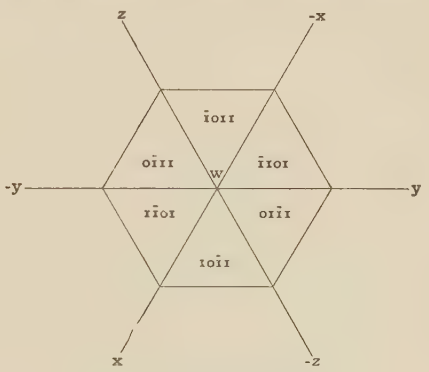


Fig. 165.—Hexagonal Bipyramid.

axes" X, Y, Z. Each of the horizontal axes, such as x, is perpendicular to the plane containing the corresponding rhombohedral axis (X) and the vertical axis w. Fig. 165 represents the same form viewed from above.

Referred to the hexagonal axes a face has not three but four indices

($hklm$). The intercepts on the three horizontal axes x, y, z are not independent of each other; if two are positive the third is negative, and its value depends upon those of the other two. The relation is such

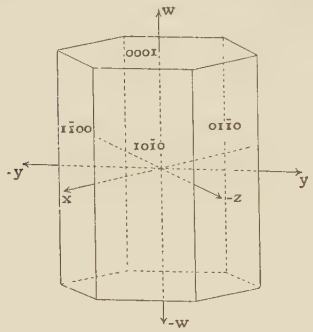


Fig. 166.—Prism: {10$\bar{1}$0} or {1$\bar{2}$1}.
(Hexagonal Axes.)

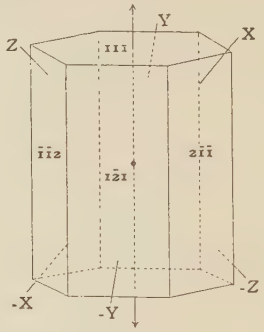


Fig. 167.—Prism: {10$\bar{1}$0} or {1$\bar{2}$1}.
(Rhombohedral Axes.)

that if two of the indices, h and k, are positive, then l is negative and equal to $h+k$. Thus with hexagonal axes the sum of the first three indices = 0.

The relations between the symbols ($hklm$) and (pqr) of a face referred to the two kinds of axes are as follows:

$$h=r-q \qquad p=k-l+m$$
$$k=p-r \qquad q=l-h+m$$
$$l=q-p \qquad r=h-k+m$$
$$m=p+q+r$$

The indices of the two hexagonal prisms (p. 71) and the basal pinakoid, when referred to the two sorts of axes, are shown in Figs. 166-169.

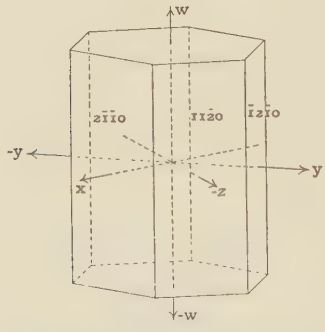


Fig. 168.—Prism: {11$\bar{2}$0} or {1$\bar{1}$0}.
(Hexagonal Axes.)

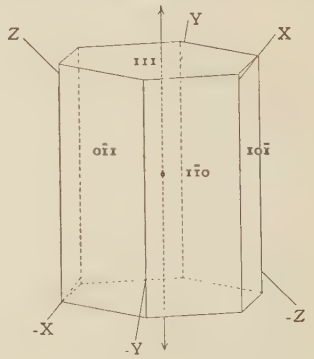


Fig. 169.—Prism: {11$\bar{2}$0} or {1$\bar{1}$0}.
(Rhombohedral Axes.)

42. **Hexagonal System — Holosymmetric Class — (Symmetry: Dihexagonal Equatorial).**—The crystals of this class possess an axis of

di-hexagonal symmetry and an equatorial plane of symmetry perpendicular to it. The seven planes of symmetry are shown in the projection (Fig. 170). It will be seen from this figure and the form $\{12\bar{3}1\}$, of which it is a projection (Fig. 171), that the class also possesses six di-digonal axes which emerge at points such as *a* and M, and a centre of symmetry.

The possible forms in this class may be deduced by considering as before the possible positions of a pole upon the projection of Fig. 170; it must lie on a side, or at an angle, of the systematic triangle *aw*M, or

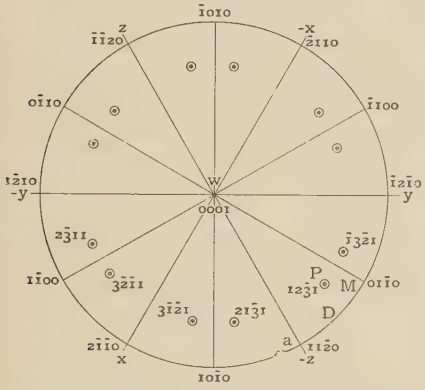


Fig. 170.—Hexagonal System, Holosymmetric Class. (Di-hexagonal Equatorial.)

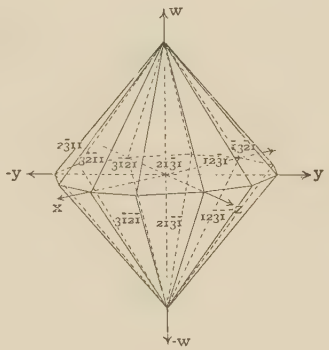


Fig. 171.—Di-hexagonal Bipyramid : $\{hklm\}$.

within the triangle, so that, as in the tetragonal system, there are seven varieties of forms :

(1) *Basal Pinakoid* $\{0001\}$.—When the pole is at *w*, the form consists of a pair of parallel faces; they are represented closing the ends of the prisms in Figs. 166, 168.

(2) *Hexagonal Prism* $\{10\bar{1}0\}$.—When the pole is at M, the form is a hexagonal prism (Fig. 166).

(3) *Hexagonal Prism* $\{11\bar{2}0\}$.—When the pole is at *a*, the form is a similar hexagonal prism (Fig. 168).

(4) *Hexagonal Bipyramid* $\{10\bar{1}1\}$.—When the pole falls upon *w*M, one side of the triangle *aw*M, the form is a hexagonal bipyramid (Fig. 172), whose horizontal edges are the same as those of Fig. 166.

(5) *Hexagonal Bipyramid* $\{11\bar{2}1\}$.—When the pole falls upon the side *wa*, the form is a hexagonal bipyramid (Fig. 173), whose horizontal edges coincide with those of Fig. 168.

(6) *Di-hexagonal Prism* $\{hkl0\}$.—When the pole falls upon the side *a*M (as at D), the form is the di-hexagonal prism of Fig. 174.

(7) *Di-hexagonal Bipyramid* $\{hklm\}$.—When the pole falls within the triangle, as at P, the form consists of twenty-four faces, and constitutes the di-hexagonal bipyramid of Fig. 171, whose horizontal edges coincide with those of Fig. 174.

Of the above forms, simple hexagonal prisms combined with the

basal pinakoid are common in beryl; but the other forms are only found in combination with each other or with the prisms and basal pinakoid.

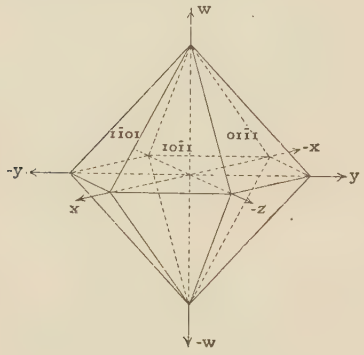


Fig. 172.—Hexagonal Bipyramid: $\{10\bar{1}1\}$.

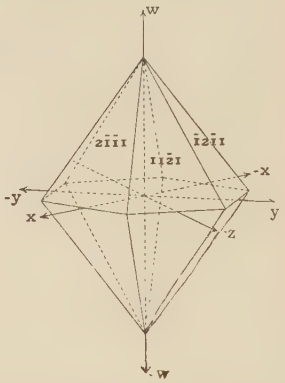


Fig. 173.—Hexagonal Bipyramid: $\{11\bar{2}1\}$.

Fig. 175 represents a crystal of beryl from Russia; $o=(0001)$, $p=(01\bar{1}1)$, $s=(11\bar{2}1)$, $m=(10\bar{1}0)$.

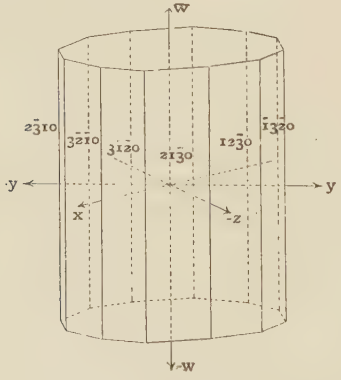


Fig. 174.—Di-hexagonal Prism: $\{hk\bar{i}0\}$.

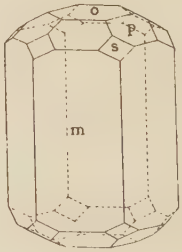


Fig. 175.—Beryl.

43. **The Calcite Class—(Symmetry: Di-hexagonal Alternating).**—The crystals of this class possess a di-hexagonal axis of alternating symmetry (see Article 22, p. 40). The figure which results from repetition of a plane about such an axis of symmetry is in general the *scalenohedron* of Fig. 177. The three planes of symmetry, shown in the projection (Fig. 176), pass through those edges which meet at its apices, and there are also three digonal axes of symmetry emerging at the points *a*. The symmetry of this class may equally well be described as due to an axis of di-trigonal symmetry, combined with a centre of symmetry, and the crystals are best referred to rhombohedral axes.

The varieties of forms possible in this class are found, as before, by considering the possible positions of a pole upon the sphere of projection.

(1) *Rhombohedron* {*hkk*}.—When the pole falls upon one of the planes of symmetry, like the poles of *e* or R (Fig. 176), the form consists of six faces,

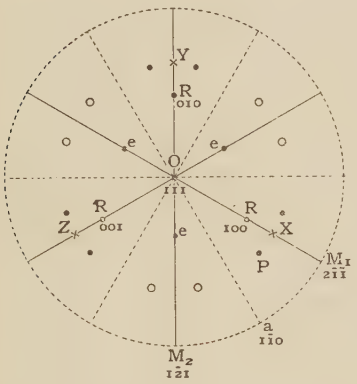


Fig. 176.—Calcite Class. (Di-hexagonal Alternating.)

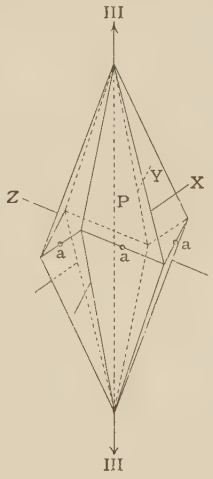


Fig. 177.—Calcite Class : {*hkl*}, Hexagonal Scalenohedron.

and is a rhombohedron (Fig. 178). When the pole falls between O and M_1 it is said to belong to a direct rhombohedron, such as Fig. 161 ; when between O and M_2, to an inverse rhombohedron, such as Fig. 163 or Fig. 178.

When the pole is nearer to the centre O than the pole of (100), the rhombohedron is "obtuse," as in Fig. 178. When further from the centre than the pole of (100), the rhombohedron is "acute," as in Fig. 179.

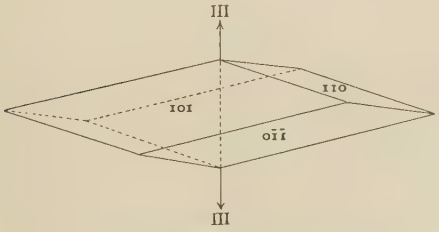


Fig. 178.—Calcite Class : {*hkk*}, Obtuse Rhombohedron.

Fig. 179.—Calcite Class: {*hkk*}, Acute Rhombohedron.

In this class a rhombohedron has two equal indices, which may be either greater or less than the third, and either positive or negative, or zero.

For a pole between R and M_1, for example, we have $m \times (100) + n \times (2\bar{1}\bar{1}) = (m+2n, -n, -n)$; the particular rhombohedron, R, whose edges are parallel to the axes, is $\{100\}$, and the general symbol for any rhombohedron is $\{hkk\}$. It must be noted that the only faces whose indices are all positive are those whose poles lie on the projection within the triangle RRR corresponding to the positive octant of the cubic projection (Fig. 103). All direct rhombohedra which are more acute than R, and all inverse rhombohedra which are more acute than *e*, must therefore have one, or two, negative indices. In Figs. 183, 184 the obtuse rhombohedron *e* truncates the edges of R, and the acute rhombohedron *s* has its edges truncated by R. Every direct rhombohedron truncates the edges of a more acute inverse rhombohedron, and has its own edges truncated by the faces of a more obtuse inverse rhombohedron.

(2) *Basal Pinakoid* $\{111\}$.—When the pole coincides with O the form is a pinakoid, as in the holosymmetric class (Figs. 167, 169).

(3) *Hexagonal Prism* $\{2\bar{1}\bar{1}\}$.—When the pole lies at M (M_1 or M_2) the form is a hexagonal prism, as in the holosymmetric class (Fig. 167).

(4) *Hexagonal Prism* $\{10\bar{1}\}$.—When the pole coincides with *a* it belongs to a hexagonal prism, as in the holosymmetric class (Fig. 169).

(5) *Di-hexagonal Prism* $\{hkl\}$, where $h+k+l=0$.—When the pole lies on the circle of projection between M and *a* it belongs to a di-hexagonal prism, as in the holosymmetric class (Fig. 174). The symbol of the zone [*a*M], found by cross-multiplying the symbols of *a* and M, is [111]. Therefore if $\{hkl\}$ is any face in this zone, $(h \times 1) + (k \times 1) + (l \times 1) = 0$ (Article 18); hence the three indices of any prism-face added together must equal 0.

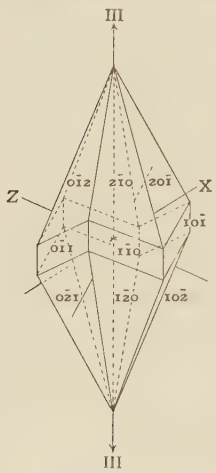


Fig. 180.

(6) *Scalenohedron* $\{hkl\}$.—When the pole lies within the triangle M_1OM_2 there is one pole in each such triangle, and this, the most general form of the calcite class, consists of twelve faces, each in general a scalene triangle; the form (Fig. 177) is therefore called a scalenohedron, and its projection P is shown in Fig. 176. The scalenohedron resembles a bipyramid in having two apices on the principal axis, and differs from a bipyramid in having six lateral edges which are not horizontal, but form a zigzag. These edges coincide with the six lateral edges of some rhombohedron; the common scalenohedra of calcite have the same lateral edges as the rhombohedron $\{100\}$. Since each lateral edge of the rhombohedron is formed by the intersection of two similar faces, it is obvious that new forms may be derived from it either by truncating or bevelling these edges; the former process gives rise, as appears from Fig. 180, to the hexagonal prism $\{10\bar{1}\}$; the latter is illustrated by Fig. 181, which shows how the rhombohedron $\{100\}$ has the same zigzag edges with the scalenohedron $\{20\bar{1}\}$, which bevels its lateral edges. The poles of $\{20\bar{1}\}$ lie in the

projection between the poles R and a, and the projection of the form is represented by P and corresponding poles in Fig. 176.

(7) *Hexagonal Bipyramid* $\{hkl\}$, where $k = \frac{h+l}{2}$. — In the particular case in which the pole falls midway between two planes of symmetry, *i.e.* in the zone [Oa], the faces at the lower end of the crystal come immediately under those at the upper end ; the edges of the scalenohedron become horizontal, and the form is converted into the hexagonal bipyramid of Fig. 182. Since a pole of this form lies between (111) and

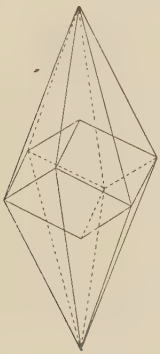


Fig. 181.

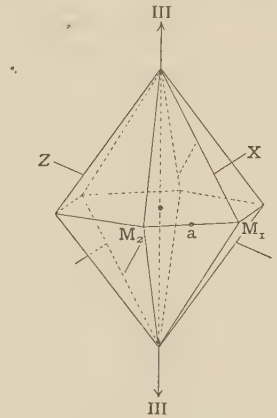


Fig. 182.—Calcite Class : Hexagonal Bipyramid.

(10$\bar{1}$), and since $m\times(111) + n\times(10\bar{1}) = (m+n,\ m,\ m-n)$—three numbers, of which the second is half the sum of the first and third —it follows that in the hexagonal bipyramid of the calcite class one index must always be the arithmetic mean of the other two.

Of the above forms, rhombohedra, both acute and obtuse, exist as isolated forms in calcite ; this mineral has also a perfect cleavage parallel to the faces of a rhombohedron, which is taken as the primitive form $\{100\}$.

The hexagonal prisms are both found as simple forms terminated by the basal pinakoid in calcite.

The scalenohedron $\{20\bar{1}\}$ is a very common simple form in the same mineral ("dog-tooth spar") ; the acute hexagonal bipyramid $\{91\bar{7}\}$ has also been found on calcite from Rhisnes in Belgium and from Visby in Sweden. The di-hexagonal prism is not known as a simple form, but is found in combination.

The close resemblance between crystals of this class and cubic crystals is well illustrated by such a combination as that of Figs. 183, 184, which is precisely analogous to that of the cube with octahedron and dodecahedron. If the whole figure were slightly elongated in the vertical direction, so that the form R became a cube, the combination would be that of the cubic system. The zones are the same as in the cubic combination, and

therefore the indices are the same. Thus the crystal is a combination of the rhombohedron R{100}, with the acute inverse rhombohedron

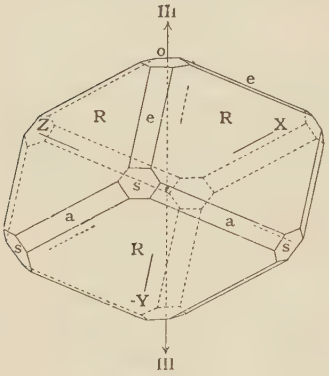


Fig. 183.

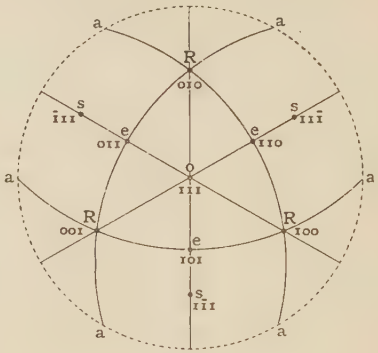


Fig. 184.

$s\{11\bar{1}\}$, the obtuse inverse rhombohedron $e\{110\}$, the hexagonal prism $a\{10\bar{1}\}$, and the basal pinakoid $o\{111\}$.

44. **The Tourmaline Class — (Symmetry: Di-trigonal Polar).** — The crystals of this class possess a polar di-trigonal axis. Repetition about this axis and its planes of symmetry gives rise to the *di-trigonal pyramid*

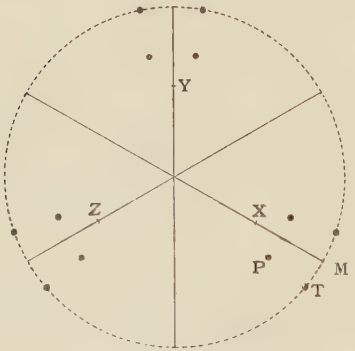


Fig. 185.—Tourmaline Class. (Di-trigonal Polar.)

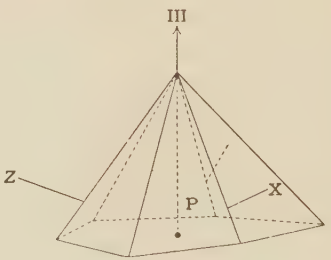


Fig. 186.—Tourmaline Class: {*hkl*}, Di-trigonal Pyramid.

of Fig. 186, shown in projection in Fig. 185. The planes of symmetry pass through its edges.

The only other forms in this class which differ from those of the preceding classes are:

(1) The form {111}, which is no longer a pinakoid but a single *basal plane*, since the di-trigonal axis is polar.

(2) The form {*hkk*}, which is not a rhombohedron but a *trigonal pyramid* (Fig. 187), having its faces perpendicular to the planes of symmetry.

(3) The form $\{2\bar{1}\bar{1}\}$, which is no longer a hexagonal but a *trigonal prism* (Fig. 189), as may be seen by imagining the pole P of Fig. 185 to

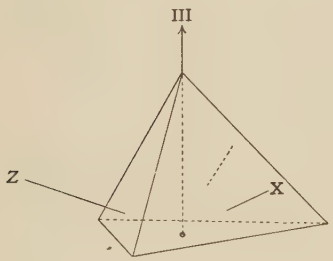


Fig. 187.—Tourmaline Class : {*hkk*}, Trigonal Pyramid.

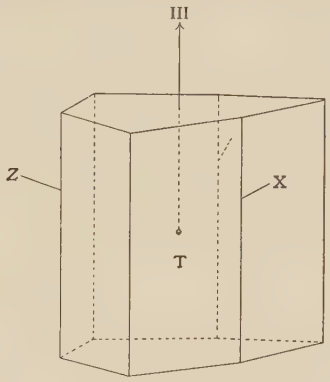


Fig. 188.—Tourmaline Class : Di-trigonal Prism.

migrate to the point M ; the remaining poles will symmetrically migrate to this and the two corresponding points.

(4) The form {*hkl*}, where $h+k+l=0$, a *di-trigonal prism* (Fig. 188).

(5) The form {*hkl*}, where $k=\frac{h+l}{2}$, a *hexagonal pyramid* (Fig. 89).

Fig. 190 represents a crystal of tourmaline from Elba—a combination

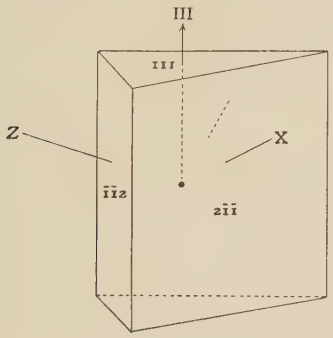


Fig. 189.—Tourmaline Class : $\{2\bar{1}\bar{1}\}$, Trigonal Prism.

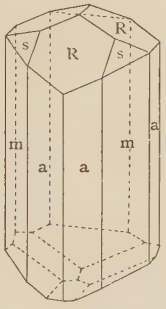


Fig. 190.—Tourmaline.[1]

of the pyramids R$\{100\}$, $s\{1\bar{1}1\}$, trigonal prism $m\{1\bar{2}1\}$, and hexagonal prism $a\{10\bar{1}\}$; at the lower end $e'\{\bar{1}\bar{1}0\}$, truncating the edges of R'$\{\bar{1}00\}$.

45. **The Dioptase Class — (Symmetry: Hexagonal Alternating).** — The crystals of this class possess an axis of alternating hexagonal symmetry. Repetition of a plane about this axis gives rise in general to a *rhombohedron* (Fig. 192), whose poles, shown in projection in Fig. 191, are not necessarily in the vertical planes containing the crystal-axes, as in the calcite

[1] The crystal of Fig. 190 has been turned through 60° about the vertical line, from the customary position corresponding to the axes of Fig. 160.

class. The only other forms belonging to this class are hexagonal prisms and the basal pinakoid.

The symmetry of this class may equally well be described as due to a trigonal axis combined with a centre of symmetry, and the crystals are referred to rhombohedral axes.

Fig. 193 represents a crystal of dioptase from the Khirgis Steppes in Siberia, a combination of the forms : R{100}, $a\{10\bar{1}\}$, $s\{70\bar{1}\}$.

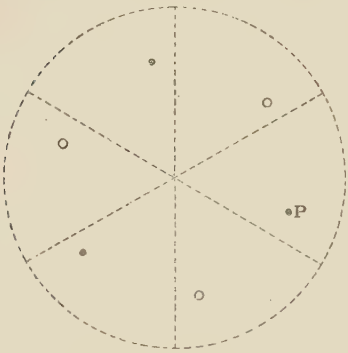


Fig. 191.—Dioptase Class. (Hexagonal Alternating.)

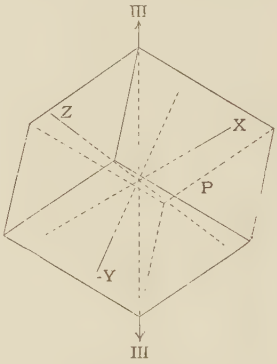


Fig. 192.—Dioptase Class : {*hkl*}, Rhombohedron.

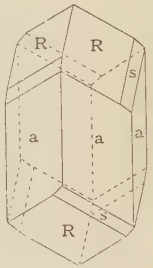


Fig. 193.—Dioptase.

46. **The Quartz Class—(Symmetry : Trigonal Holoaxial).**—The crystals of this class possess an axis of trigonal symmetry, and are holoaxial, or

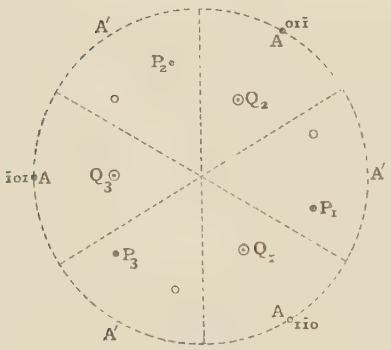


Fig. 194.—Quartz Class. (Trigonal Holoaxial.)

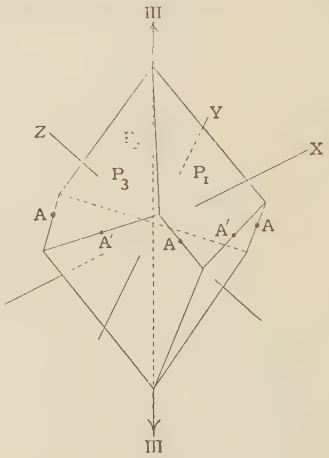


Fig. 195.—Quartz Class : {*hkl*}, Trigonal Trapezohedron.

possess three polar digonal axes perpendicular to the principal axis. Repetition of a plane about these elements of symmetry gives rise to the *trigonal trapezohedron* of Fig. 195 (shown in projection in Fig. 194). The digonal axes emerge at the points A.

The other form in this class, which differs from forms previously considered in the hexagonal system, is the *trigonal bipyramid* of Fig. 196, whose poles, Q, lie in vertical zones through A, so that the faces intersect

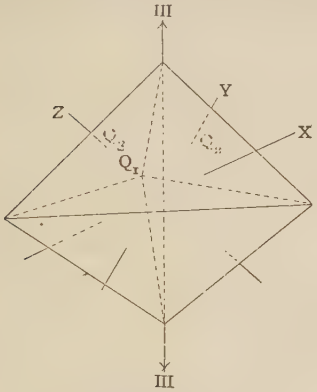


Fig. 196.—Quartz Class: Trigonal Bipyramid.

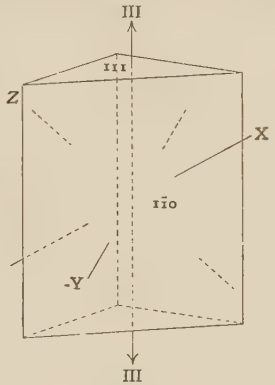


Fig. 197.—Quartz Class: $\{1\bar{1}0\}$, Trigonal Prism.

in horizontal edges, and not obliquely as in Fig. 195. Its edges are identical with those of the base of the *trigonal prism* $\{1\bar{1}0\}$ (Fig. 197), and its indices are $\{hkl\}$, where $k=\frac{h+l}{2}$.

It must be observed that $\{2\bar{1}\bar{1}\}$ is the trigonal prism in the tourmaline class and $\{1\bar{1}0\}$ is the trigonal prism in the quartz class.

Fig. 198 represents a crystal of quartz, which is a combination of the rhombohedron R$\{100\}$, with the inverse rhombohedron $z\{2\bar{1}2\}$, the hexagonal prism $m\{2\bar{1}\bar{1}\}$, the trigonal bipyramid s, and the trapezohedron x.

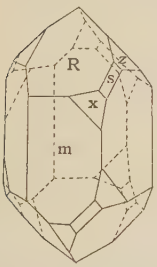


Fig. 198.—Quartz, right-handed crystal.[1] R$\{100\}$, $s\{41\bar{2}\}$, $m\{2\bar{1}\bar{1}\}$, $x\{4\bar{1}\bar{2}\}$.

Crystals of the quartz class, like all holoaxial crystals, have neither a plane nor a centre of symmetry. Hence, like those of the cuprite class, they are enantiomorphous. The reflection of the crystal of Fig. 198 in a mirror would have the appearance of Fig. 199, which bears the same relation to Fig. 198 that a left hand bears to a right hand. Both sorts of crystals are known.

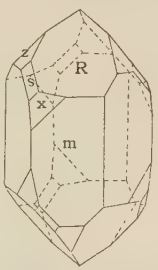


Fig. 199.—Quartz, left-handed crystal.[1] R$\{100\}$, $s\{42\bar{1}\}$, $m\{2\bar{1}\bar{1}\}$, $x\{42\bar{1}\}$.

Fig. 198 is called a right-handed crystal of quartz.

Fig. 199 is called a left-handed crystal of quartz.

A projection of the forms of quartz (left-handed crystal) is given in Fig. 559, p. 423.

[1] The crystals of Figs. 198 and 199 have been turned through 60° about the vertical line, from the customary position corresponding to the axes of Fig. 160.

47. **The Greenockite Class — (Symmetry: Di-hexagonal Polar).** — The crystals of this class possess a polar di-hexagonal axis. Repetition of a plane about this axis and its planes of symmetry gives rise to the di-hexagonal pyramid of Fig. 201; the planes of symmetry pass through its edges, as shown in the projection (Fig. 200). Forms corresponding to the

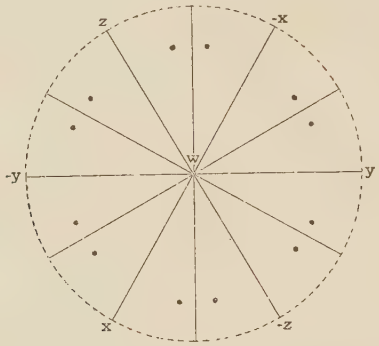


Fig. 200.—Greenockite Class. (Di-hexagonal Polar.)

bipyramids of the holosymmetric class are here all *pyramids*, and the form {0001} is a single *basal plane* and not a pinakoid. Fig. 202 represents a crystal of greenockite from Renfrewshire—a combination of the hexagonal pyramids $z\{20\bar{2}1\}$, $x\{10\bar{1}1\}$, $i\{10\bar{1}2\}$, $x'\{10\bar{1}\bar{1}\}$, with the basal plane $\{000\bar{1}\}$, and the hexagonal prism $m\{10\bar{1}0\}$.

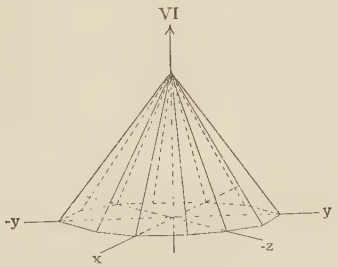


Fig. 201.—Greenockite Class: {*hklm*}, Di-hexagonal Pyramid.

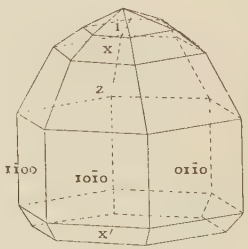


Fig. 202.—Greenockite.

48. **The Apatite Class — (Symmetry: Hexagonal Equatorial).** — The crystals of this class possess a hexagonal axis perpendicular to an equatorial plane of symmetry, and are therefore also centro-symmetrical. Repetition of a plane about these elements of symmetry leads in the general case to a *hexagonal bipyramid* (Fig. 204, projected in Fig. 203), whose corners are not necessarily on the horizontal axes x y z, nor its horizontal edges perpendicular to them, as was the case in Figs. 172 and 173.

The other forms of this class are hexagonal prisms and the basal

pinakoid. Fig. 205 represents a crystal of apatite from the St. Gothard, a combination of the basal pinakoid $o\{0001\}$ and hexagonal prism $m\{10\bar{1}0\}$, with the hexagonal bipyramids $x\{10\bar{1}1\}$, $s\{11\bar{2}1\}$, $\mu\{21\bar{3}1\}$.

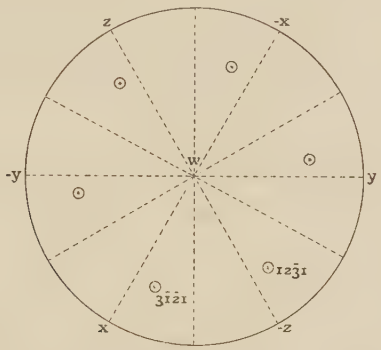


Fig. 203.—Apatite Class. (Hexagonal Equatorial.)

If the form μ were not present, this crystal would present the appearance of one having six vertical planes of symmetry.[1]

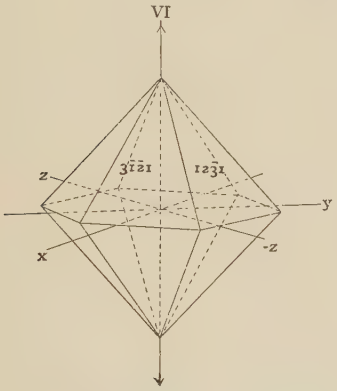


Fig. 204.—Apatite Class : $\{hklm\}$, Hexagonal Bipyramid.

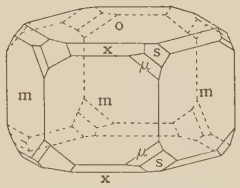


Fig. 205.—Apatite.

49. **The Axial Ratio or the Axial Angle.**—With the rhombohedral axes the parameters are equal, as determined by the intercepts made by the basal plane (111) ; but the angle which the axes make with one another is not a right angle, as it is in the cubic system. It is the plane angle of the rhombohedron $\{100\}$ of Fig. 160, just as in the cubic system it is the plane angle of the cube. In Fig. 184 it is the supplement of the angle at R between two zones R *e* R. The axial angle is denoted by α.

[1] For the five remaining classes of the hexagonal system : Hexagonal Holoaxial and Hexagonal Polar, Di-trigonal Equatorial, Trigonal Equatorial, and Trigonal Polar, see pp. 91, 92.

In the system of hexagonal axes the length of the principal axis is denoted by c and that of the three lateral axes by a.

Then in Fig. 206—

$$\frac{c}{a}=\frac{OC}{OA}.$$

But $OA=\frac{2}{\sqrt{3}}OM$, from the plane triangle OAM (Fig. 207), since $MOA=30°$.

Also,

$$\frac{OC}{OM}=\tan CMO.$$

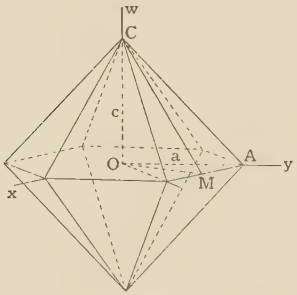


Fig. 206.

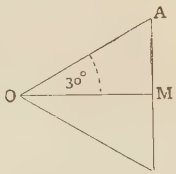


Fig. 207.

But CMO is the angle between the line CM in the plane $(01\bar{1}1)$ and the line OM in the basal plane (0001), which is equal to the angle $(01\bar{1}1 : 0001)$.

Hence

$$\frac{c}{a}=\frac{OC}{OA}=\frac{\sqrt{3}}{2}\,\frac{OC}{OM}=\frac{\sqrt{3}}{2}\,.\tan(01\bar{1}1 : 0001).$$

The axis a is generally taken as unity.

The Monoclinic System

The crystals of this system possess one axis of twofold symmetry, or one symmetry-plane, or both, and are referable to three unequal axes, one of which is perpendicular to the other two.

50. **Monoclinic System — Holosymmetric Class — (Symmetry: Digonal Equatorial).** — The crystals of this class possess a digonal axis which is perpendicular to a plane of symmetry. The manner in which crystals belonging to this system are drawn and projected is shown in Figs. 208 and 209.

The axes are chosen so that one of them is parallel and two are perpendicular to the symmetry-axis. The two latter axes lie in the plane of symmetry and are inclined to each other at some angle other than 90°. The symmetry-axis is chosen as Y (b-axis); of the two remaining axes one, Z (c-axis), is placed vertical, and the other, X (a-axis), so that the upper

obtuse axial angle is in front (Fig. 209). In the projection the plane of symmetry XZ, which contains the a- and c-axes, is placed in the plane of the paper, so that Y, which coincides with the pole of B (010), lies

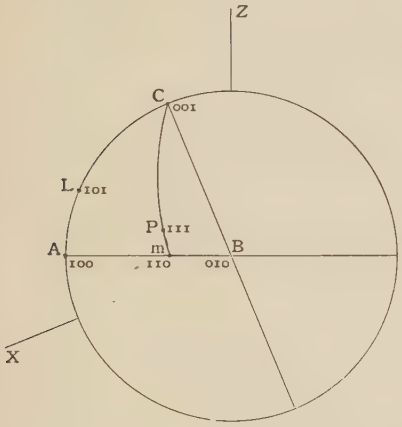


Fig. 208.—Method of Projecting a Monoclinic Crystal.

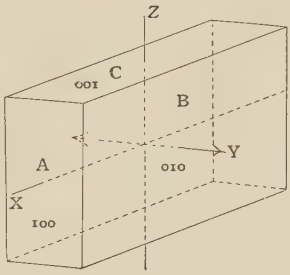


Fig. 209.—The Axial Pinakoids.

at the centre of the projection, and the upper obtuse angle is on the left; the crystal being placed as in Fig. 210. X and Z are the directions in which the a- and c-axes emerge from the sphere of projection; their points of emergence do not coincide with the poles of any faces of the crystal, whereas in the three rectangular systems they coincide, as was seen above, with the poles of (100) and (001).

The axis Y, which is perpendicular to the vertical axis, is called the "orthodiagonal." The axis X, which is inclined to the vertical axis, is called the "clinodiagonal."

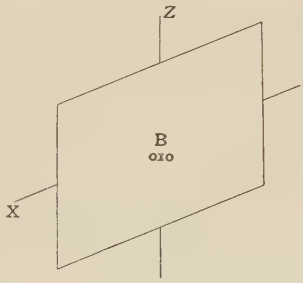


Fig. 210.

In the monoclinic system there are no closed forms. The possible forms in the holosymmetric class are as follows:

(1) *Ortho-pinakoid* {100}.—When the pole is at A the form consists of a pair of faces parallel to the orthodiagonal and to the vertical axis.

(2) *Clino-pinakoid* {010}.—When the pole is at B the form consists of a pair of faces parallel to the clino-diagonal and to the vertical axis.

(3) *Basal Pinakoid* {001}.—When the pole is at C the form consists of a pair of faces parallel to the ortho- and clino-diagonals.

A combination of these three forms (whose intersections determine the directions of the axes) is shown in Fig. 209.

Forms whose faces replace the edges of Fig. 209, and whose poles therefore lie on the sides of the triangle ABC, are parallel to one of the three axes.

(4) *Prism* {*hk*0}.—When the pole lies between A and B, as at *m*, the form consists of four faces parallel to the vertical axis (Fig. 211) and is

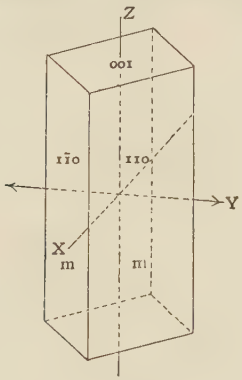


Fig. 211.—Prism: {*hk*0}, with Basal Pinakoid.

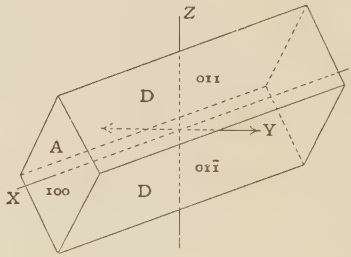


Fig. 212.—Prism: {0*kl*}, with Ortho-pinakoid.

a prism with a rhombic base. The particular prism whose faces pass through the extremities of the lateral axes is {110}. Such a form is shown in combination with the basal pinakoid in Fig. 211; the basal planes are oblique to the prism-faces.

(5) *Prism* {0*kl*}.—When the pole falls between B and C, the form

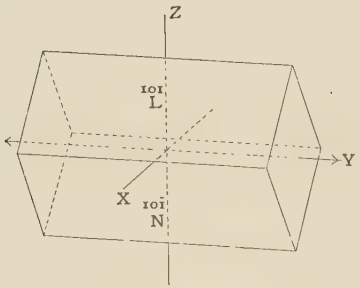


Fig. 213.—Combination of two Pinakoids: {*h*0*l*} and {*h*0$\bar{l}$}, with Clino-pinakoid.

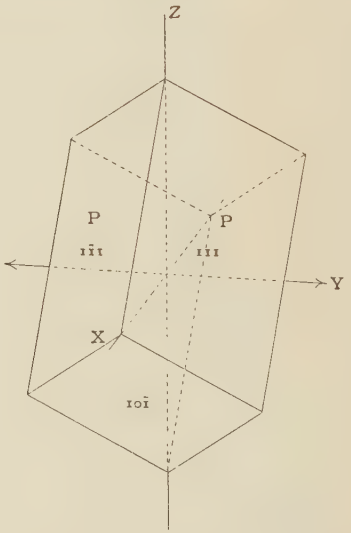


Fig. 214.—Prism {*hkl*} with a Pinakoid {*h*0$\bar{l}$}.

consists of four faces parallel to the clino-diagonal and constituting a prism. The prism whose faces pass through the extremities of the

b- and *c*-axes has the symbol {011}. Such a form is shown in combination with the ortho-pinakoid in Fig. 212; its faces are oblique to the ortho-pinakoid.

(6) *Pinakoid* {*h*0*l*}.—When the pole falls between A and C, as at L, the faces constitute a pinakoid parallel to the ortho-diagonal. The form whose faces pass through the positive extremities of the *a*- and *c*-axes has the symbol {101} (Fig. 213).

(7) *Prism* {*hkl*}.—When the pole falls within the triangle ABC, as at P, the form has four faces and is a prism or "hemi-pyramid" whose faces meet all three axes (Fig. 214). The form whose faces pass through the positive extremities of the three axes has the symbol {111}.

A combination of the two prisms {*hkl*} and {*hkl*} resembles a bipyramid, as in Fig. 215, which really consists of the two forms P{111} and Q{11$\bar{1}$}.

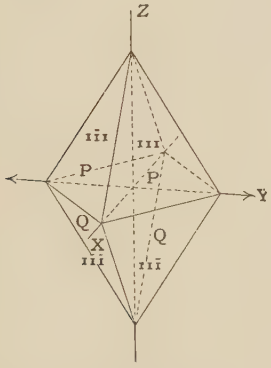


Fig. 215.—Monoclinic "Bipyramid," consisting of the two Prisms {*hkl*} and {*hkl*}.

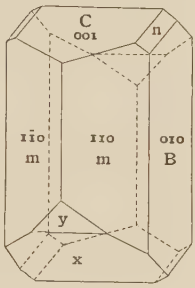


Fig. 216.—Orthoclase.

Similarly Fig. 213 represents a combination of the two pinakoids L{101} and N{10$\bar{1}$}, which resembles a prism. Such combinations are of common occurrence in crystals of this class.

Faces parallel to the ortho-diagonal and clino-diagonal are often called "ortho-domes" and "clino-domes," respectively.

Fig. 216 represents a crystal of orthoclase from Colorado, a combination of the clino-pinakoid B, basal pinakoid C, prism *m*{110}, "clino-dome" *n*{011}, "ortho-domes" *x*{10$\bar{1}$} and *y*{20$\bar{1}$}.

51. **The Clinohedrite Class — (Symmetry: Planar).** — The crystals of this class possess one plane of symmetry only, and no axis or centre of symmetry. The general form consists of a pair of faces equally inclined to the plane of symmetry and forming a *dome* (see p. 47). Other possible forms are the *pinakoid* (whose faces are parallel to the plane of symmetry) and the single plane or *pedion* (faces perpendicular to the plane of symmetry).

This type of symmetry is illustrated by crystals of clinohedrite, a silicate of lime and zinc from New Jersey (Fig. 217), which shows a

combination of the pinakoid $b\{010\}$, with two pedia, $e\{101\}$ and $e'\{\bar{1}0\bar{1}\}$, and a number of domes: $p\{111\}$, $h\{320\}$, $m\{110\}$, $n\{120\}$, etc.[1]

52. **The Axial Ratios and the Axial Angle.**—The lengths of the axes are most conveniently obtained from the angles of a pair of parametral

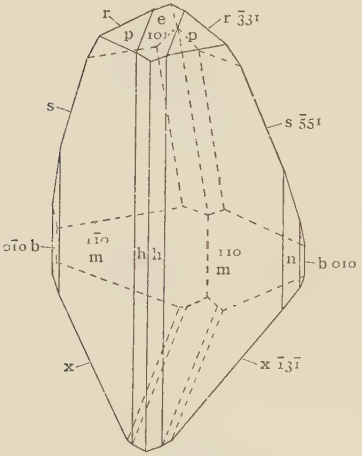


Fig. 217.—Clinohedrite.

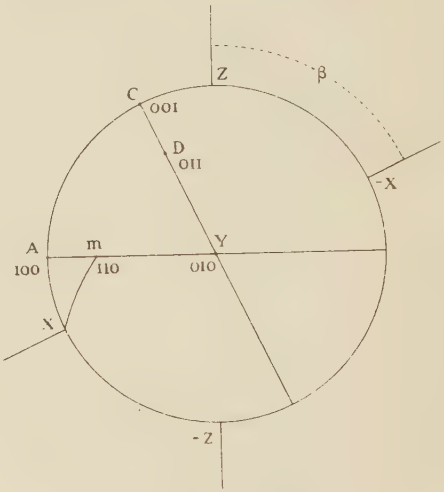


Fig. 218.—Monoclinic System.

forms, each of which cuts two axes, *e.g.* the prism D{011} and the prism $m\{110\}$ (Fig. 218).

Thus,
$$\frac{a}{1}\cos mX = \frac{b}{1}\cos mY$$

$$\therefore \frac{a}{b} = \frac{\cos mY}{\cos mX}.$$

But, from the right-angled triangle mAX,

$$\cos mX = \cos Am \,.\, \cos AX = \cos Am \,.\, \sin AC,$$

and, since $AY = 90°$, $\cos mY = \sin Am$

$$\therefore \frac{a}{b} = \frac{\tan Am}{\sin AC}.$$

Similarly,
$$\frac{c}{b} = \frac{\tan CD}{\sin AC}.$$

The acute angle between the axes X and Z is always called β; the crystalline form is defined by the axial ratios $a : b : c$ and the axial angle β; the latter can often be found by direct measurement, since it is equal to the angle between the faces A and C. The axis b is taken as unity.

[1] For the remaining monoclinic class, Digonal Polar, see pp. 91, 92.

The Anorthic System

The crystals of this system possess no more than centro-symmetry, and are referable only to three unequal oblique axes.

53. **Anorthic System—Holosymmetric Class—(Symmetry: Central).** — The three axes in this system being not only unequal in length, but also inclined to each other at different angles, none of which is a right angle, the points X, Y, Z, at which the axes emerge from the sphere of projection cannot coincide with the poles of any faces upon the crystal (Fig. 219). Since there is a centre of symmetry but no plane or axis of symmetry,

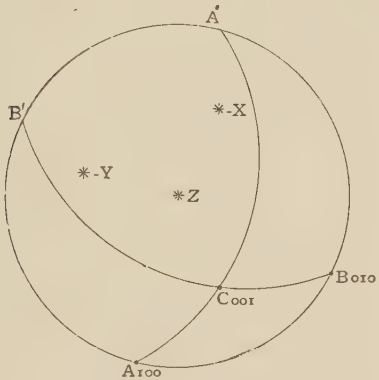


Fig. 219.—Method of Projecting an Anorthic Crystal.

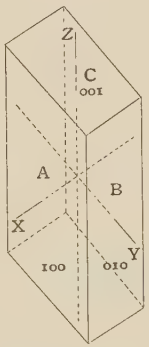


Fig. 220.—The Axial Pinakoids.

all the forms are *pinakoids*, consisting of a single pair of parallel faces. Three of these, having been arbitrarily chosen as {100}, {010} and {001}, respectively, give by their intersections the directions of the axes (Fig. 220); the axial lengths are then determined by the positions, either of two faces which replace two of these edges (each therefore making intercepts upon only two axes), or of one face which replaces one of the corners (intersecting all the three axes).

It is generally convenient (as in the orthorhombic system) to arrange that the shorter of the two lateral axes shall be directed towards the observer, and that (as in the monoclinic system) the upper obtuse angle between the *a*- and *c*-axes shall be in front.

The *a*- and *c*-axes are called the brachy-diagonal and macro-diagonal respectively, and the three axial pinakoids are distinguished as the macro-, brachy- and basal pinakoids.

Pairs of forms parallel to the vertical axis are often called "prisms"; forms parallel to one of the two lateral axes, though really pinakoids, are usually called "domes"; forms which intersect all three axes (and whose poles therefore lie inside one of the triangles ABC, A'BC, etc.) are in the same way usually called "pyramids."

The complete doubly oblique " bipyramid " whose faces pass through the extremities of all the three oblique axes (Fig. 221) consists in reality of four distinct pinakoid forms $\{111\}$, $\{11\bar{1}\}$, $\{1\bar{1}1\}$, $\{1\bar{1}\bar{1}\}$.

Fig. 222 represents a crystal of axinite from Dauphiné, a combination of the forms M$\{1\bar{1}0\}$, A$\{100\}$, $m\{110\}$, $r\{1\bar{1}1\}$, $s\{201\}$, $x\{111\}$.

54. **The Axial Ratios and Angles.** — In the anorthic system it is necessary to ascertain from measurements both the lengths and the

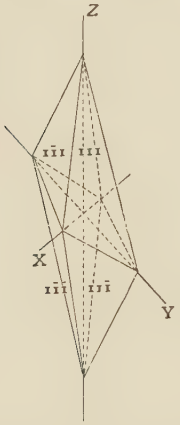


Fig. 221.—Anorthic " Bipyramid " consisting of Four Pinakoids.

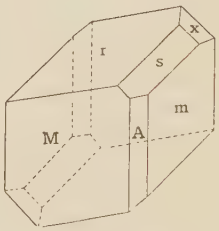


Fig. 222.—Axinite.

directions of the three axes; there are therefore three axes, a, b, c, and also three axial angles, $\alpha = ZY$, $\beta = XZ$, $\gamma = XY$,[1] to be determined. None of these can be found by direct measurement; they must all be calculated from five or more independent angles, as shown on p. 38; α, β, γ are the plane angles of Fig. 220. The axis b is taken as unity.

In the preceding pages only those twenty-two classes of crystals have been described which are satisfactorily represented among minerals. In addition to these, the following ten classes are also possible:

Symmetry.	*System.*
Di-tetragonal polar	Tetragonal.
Tetragonal holoaxial	
Tetragonal alternating	
Hexagonal holoaxial	Hexagonal.
Hexagonal polar	
Di-trigonal equatorial	
Trigonal equatorial	
Trigonal polar	
Digonal polar	Monoclinic.
No symmetry	Anorthic.

A complete summary of the thirty-two classes is given below in the Appendix to this chapter.

[1] α, β, γ are the supplements of the angles so lettered in Fig. 63, p. 34.

APPENDIX

THE THIRTY-TWO CLASSES OF CRYSTALS

It can be proved that only four sorts of axes of symmetry are compatible with the law of rational indices, namely, digonal, trigonal, tetragonal, hexagonal axes, and that consequently only these four sorts of axes are possible in crystals.

All the parts of the crystal are brought into the position previously occupied by equivalent parts, by a rotation of—

180°	about a	digonal axis
120°	,,	trigonal axis
90°	,,	tetragonal axis
60°	,,	hexagonal axis.

Hence, if there be another axis of symmetry inclined to an n-gonal axis, there must be n such axes; or if there be a plane of symmetry inclined to the n-gonal axis there must be n such planes.

The above axes, together with the plane of symmetry and the centre of symmetry, constitute the elements of symmetry possible in crystals.

An n-gonal axis may exist alone, or it may be accompanied simply by axes of digonal symmetry perpendicular to it (without planes of symmetry); the symmetry is then called holoaxial: *e.g.* the trigonal axis of quartz (Fig. X, p. 92).

An n-gonal axis may be the intersection of planes of symmetry; the symmetry is then called di-n-gonal: *e.g.* the di-trigonal axis of tourmaline (Fig. XII).

An n-gonal axis may be perpendicular to a plane of symmetry; the symmetry is then called equatorial: *e.g.* the tetragonal axis of scheelite (Fig. XXIV).

An n-gonal axis may operate simultaneously with an equatorial plane (as explained on p. 40): the symmetry is then called alternating: *e.g.* the hexagonal axis of dioptase (Fig. XV), or the di-hexagonal axis of calcite (Fig. XIX).

An n-gonal axis which is perpendicular neither to a plane of symmetry, nor to an axis of even symmetry, is called polar.

A crystal may be devoid of axes of symmetry, and it may then either be entirely without symmetry, or it may possess a plane of symmetry only. A digonal alternating axis is equivalent to a centre of symmetry.

By applying the above considerations to the four sorts of axes, twenty-five classes of symmetry can be deduced. Five further classes are found by considering how axes of symmetry which are not at right angles can be combined; three tetragonal or three digonal axes at right angles can be combined with a trigonal axis, equally inclined to them, and in that case involve the presence of three more trigonal axes similarly disposed and inclined to one another at 70° 32′. This leads to the cubic system, which is characterised by four trigonal axes, or, as it may be called, "tesseral symmetry" (p. 42). In one further class there is a single plane of symmetry but no axis. Any other combination of the above elements of symmetry which may be devised will be found either to be identical with one of those already obtained, or to involve the presence of other elements of symmetry which cannot exist in crystals. One other class

is possible, in which no element of symmetry is present, bringing the total number up to thirty-two.

In the figures, I to XXXII, given below, each class is represented by a simple form or combination belonging to it (usually a prism). The order of the principal axis (where present), and consequently the system, is at once seen from the shape of the prism, and the true symmetry of each class is indicated by marks on the faces corresponding in form and orientation to the pits produced by etching (see Chapter V, p. 125). A comparison of the various figures shows how the same form may occur in all the classes of a system but may be distinguished by etching; any substance belonging to the cubic system may crystallise in cubes, and any belonging to the tetragonal system may crystallise in square prisms.

The marks representing etching pits are as follows:

(unsymmetrical), denoting a face which is not perpendicular to a plane or axis of symmetry.

(symmetrical about a centre), denoting a face perpendicular to a digonal axis.

(symmetrical about two lines), denoting a face perpendicular to a di-digonal axis.

denoting a face perpendicular to a tetragonal or di-tetragonal axis.

 (symmetrical about one line), denoting a face perpendicular to a single plane of symmetry.

In the following table the third column gives the name of the most general form $\{hkl\}$ characteristic of each class, *i.e.* the form obtained by repeating a plane about the elements of symmetry given in the preceding column. Many authors name the classes after these forms; for example, Class X is called the trigonal trapezohedral class, Class XXVIII the tetrahedral-pentagonal-dodecahedral class.

The whole system of classes can easily be recovered by considering the possible cases in order, thus: (1) No symmetry; (2) a centre of symmetry; (3) a plane of symmetry; (4) a digonal axis; (5) a trigonal axis; (6) a hexagonal axis; (7) a tetragonal axis; (8) four trigonal axes.

In (4) to (7) the characteristic axis may be polar, alternating, holoaxial, or equatorial, and may be n-gonal or di-n-gonal. It must be noticed, however, that a di-n-gonal axis cannot occur in holoaxial crystals, since it involves planes of symmetry.

In the cubic system (8) the tesseral symmetry may be either polar, holoaxial, or central: di-tesseral symmetry may be either polar or central.

[TABLE

System.	Symmetry of the Class.	Name of the General Form {*hkl*}.	Figure.	Example.
Anorthic	I. Asymmetric	Pedion	Fig. 1.	1. *Calcium thiosulphate.*
Anorthic	II. Central	Pinakoid (Fig. 87)	,, II.	2. *Axinite.*
Monoclinic	III. Planar	Dome (Fig. 94)	,, III.	3. *Clinohedrite.*
Monoclinic	IV. Digonal polar	Sphenoid (Fig. 95)	,, IV.	4. *Tartaric acid.*
	,, alternating = II.			
Monoclinic	V. ,, equatorial	Prism (Fig. 93)	,, V.	5. *Gypsum.*
Orthorhombic	VI. ,, holoaxial	Bisphenoid (Fig. 150)	,, VI.	6. *Sulphur.*
Orthorhombic	VII. Di-digonal polar	Rhombic pyramid (Fig. 153)	,, VII.	7. *Hemimorphite.*
	,, alternating = V.			
Orthorhombic	VIII. ,, equatorial	Rhombic bipyramid (Fig. 148)	,, VIII.	8. *Barytes.*
Hexagonal	IX. Trigonal polar	Trigonal pyramid (*cf.* Fig. 187)	,, IX.	9. *Sodium periodate.*
	,, alternating = XI.			
Hexagonal	X. ,, holoaxial	Trigonal trapezohedron (Fig. 195)	,, X.	10. *Quartz.*
Hexagonal	XI. ,, equatorial	Trigonal bipyramid (*cf.* Fig. 196)	,, XI.	11.
Hexagonal	XII. Di-trigonal polar	Di-trigonal pyramid (Fig. 186)	,, XII.	12. *Tourmaline.*
	,, alternating = XIII.			
Hexagonal	XIII. ,, equatorial	Di-trigonal bipyramid	,, XIII.	13. *Benitoite.*
Hexagonal	XIV. Hexagonal polar	Hexagonal pyramid (Fig. 89)	,, XIV.	14. *Nepheline* (?).
Hexagonal	XV. ,, alternating	Rhombohedron (Fig. 192)	,, XV.	15. *Dioptase.*
Hexagonal	XVI. ,, holoaxial	Hexagonal trapezohedron	,, XVI.	16. *Barium stibiotartrate*
Hexagonal	XVII. ,, equatorial	Hexagonal bipyramid (Fig. 204)	,, XVII.	17. *Apatite.* [+*pot. nitr.*
Hexagonal	XVIII. Di-hexagonal polar	Di-hexagonal pyramid (Fig. 201)	,, XVIII.	18. *Greenockite.*
Hexagonal	XIX. ,, alternating	Hexagonal scalenohedron (Fig. 177)	,, XIX.	19. *Calcite.*
Hexagonal	XX. ,, equatorial	Di-hexagonal bipyramid (Fig. 171)	,, XX.	20. *Beryl.*
Tetragonal	XXI. Tetragonal polar	Tetragonal pyramid (Fig. 139)	,, XXI.	21. *Wulfenite.*
Tetragonal	XXII. ,, alternating	Tetragonal bisphenoid (*cf.* Fig. 132)	,, XXII.	22.
Tetragonal	XXIII. ,, holoaxial	Tetragonal trapezohedron	,, XXIII.	23. *Strychnine sulphate.*
Tetragonal	XXIV. ,, equatorial	Tetragonal bipyramid (Fig. 135)	,, XXIV.	24. *Scheelite.*
Tetragonal	XXV. Di-tetragonal polar	Di-tetragonal pyramid	,, XXV.	25. *Iodosuccinimide.*
Tetragonal	XXVI. ,, alternating	Tetragonal scalenohedron (Fig. 131)	,, XXVI.	26. *Chalcopyrite.*
Tetragonal	XXVII. ,, equatorial	Di-tetragonal bipyramid (Fig. 127)	,, XXVII.	27. *Zircon.*
Cubic	XXVIII. Tesseral polar	Tetrahedral pentagonal dodecahedron (Fig. 120)	,, XXVIII.	28. *Ullmannite.*
Cubic	XXIX. ,, holoaxial	Pentagonal icositetrahedron (Fig. 116)	,, XXIX.	29. *Cuprite.*
Cubic	XXX. ,, central	Dyakis-dodecahedron (Fig. 112)	,, XXX.	30. *Pyrites.*
Cubic	XXXI. Di-tesseral polar	Six-faced tetrahedron (Fig. 106)	,, XXXI.	31. *Tetrahedrite.*
Cubic	XXXII. ,, central	Six-faced octahedron (Fig. 102)	,, XXXII.	32. *Galena.*

Fig. I.
Asymmetric.

Fig. II.
Central.

Fig. III.
Planar.

Fig. IV.
Digonal Polar.

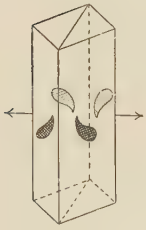


Fig. V.
Digonal Equatorial.

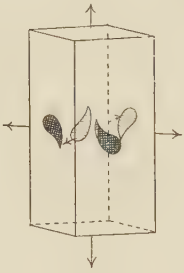


Fig. VI.
Digonal Holoaxial.

Fig. VII.
Di-digonal Polar.

Fig. VIII.
Di-digonal Equatorial.

Fig. IX.
Trigonal Polar.

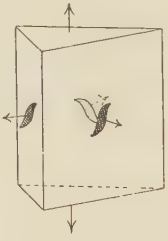


Fig. X.
Trigonal Holoaxial.

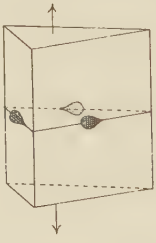


Fig. XI.
Trigonal Equatorial.

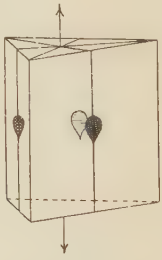


Fig. XII.
Di-trigonal Polar.

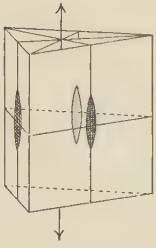


Fig. XIII.
Di-trigonal Equatorial.

Fig. XIV.
Hexagonal Polar.

Fig. XV.
Hexagonal Alternating.

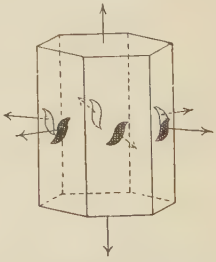


Fig. XVI.
Hexagonal Holoaxial.

THE SYMMETRY OF THE 32 CLASSES ILLUSTRATED BY ETCHED FORMS.

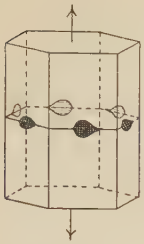


Fig. XVII.
Hexagonal Equatorial.

Fig. XVIII.
Di-hexagonal Polar.

Fig. XIX.
Di-hexagonal Alternating.

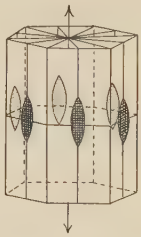


Fig. XX.
Di-hexagonal Equatorial.

Fig. XXI.
Tetragonal Polar.

Fig. XXII.
Tetragonal Alternating.

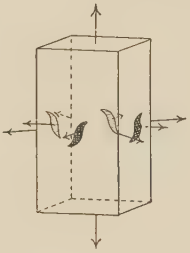


Fig. XXIII.
Tetragonal Holoaxial.

Fig. XXIV.
Tetragonal Equatorial.

Fig. XXV.
Di-tetragonal Polar.

Fig. XXVI.
Di-tetragonal Alternating.

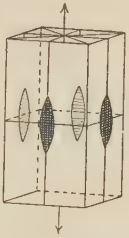


Fig. XXVII.
Di-tetragonal Equatorial.

Fig. XXVIII.
Tesseral Polar.

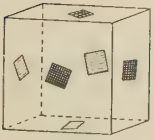


Fig. XXIX.
Tesseral Holoaxial.

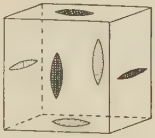


Fig. XXX.
Tesseral Central.

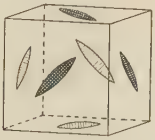


Fig. XXXI.
Di-tesseral Polar.

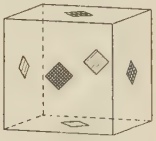


Fig. XXXII.
Di-tesseral Central.

THE SYMMETRY OF THE 32 CLASSES ILLUSTRATED BY ETCHED FORMS.

CHAPTER II

THE REGULAR CONJUNCTION OF CRYSTALS

Some minerals are only found in Nature as isolated crystals, but the majority occur in groups which may be either regular or irregular. The conjunction of two or more crystals is said to be "regular" when they are so united that certain parts of each are parallel to certain parts of its neighbour; two crystals so related may belong either to the same or to different species. Irregular modes of grouping ("radiating," "rosette-shaped," etc.) will be described later (see p. 307).

There are three types of regular conjunction.

1. **Parallel Growth.** — In the first place, if *all* the parts (edges and faces) of one crystal are parallel to all the corresponding parts of its neighbour, the two crystals are completely parallel. Except in the cubic system this is, of course, only possible for crystals of the same mineral; in the other systems different minerals have different interfacial angles and therefore cannot have all their faces parallel at the same time; though in either the tetragonal or hexagonal system two crystals of different minerals may conceivably be so united as to have all their *prism* faces and their basal planes parallel.

"Parallel growth," even on a very minute scale, may easily be recognised by the simultaneous reflection of the light from all the parallel faces of the group. One frequent instance of parallel growth is that afforded by crystals with "drusy" faces (see p. 306); each drusy face is covered with a number of minute crystals (so-called "sub-individuals"), which are generally parallel to each other and lie nearly in a plane. Drusy faces of this sort reflect light simultaneously from detached points all over their surface, that is, from the facets of the sub-individuals, and this gives rise to a peculiar sheen as the crystal is turned about in the hand. It not infrequently happens that the crystals of a mineral are covered or partly covered with a later deposit of the same mineral, in which the more recent individuals, though parallel to the original crystals, show an entirely different combination of forms, owing perhaps to the fact that they have crystallised under changed conditions. A good example of this is afforded by the large octahedral crystals of fluor from several parts of Cornwall, notably the neighbourhood of Redruth, which appear as if built up of numerous minute cubes ranged in parallel positions, but

which in fact represent an octahedral crystal on the surface of which small cubic crystals have been deposited (Fig. 446, p. 307). The cubes are really parallel to the octahedral nucleus, as shown by the fact that

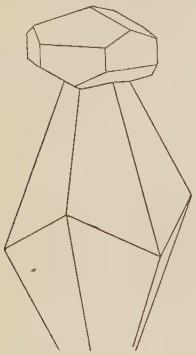


Fig. 223.—Calcite.

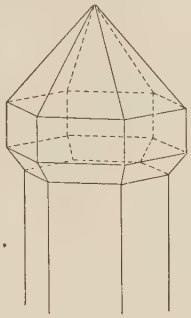


Fig. 224.—Sceptre Quartz.

their cleavages are parallel to those of the latter. In the so-called "nail-head spar" of Cumberland (Fig. 223), scalenohedra of calcite $\{20\bar{1}\}$ are terminated by rhombohedra whose cleavages are parallel to those of the scalenohedron, so that the two crystals are really parallel, although no extant face of the one is parallel to any extant face of the other. Or, again, one crystal may simply differ from the other in the relative *size* of its faces. "Sceptre quartz" is the name given to thin prisms of quartz which are capped by stouter crystals, as is the case with some of the amethyst from Mursinka (Fig. 224).

In Fig. 225 is represented a curious example of parallel growth illustrated by copper from Lake Superior, as described by E. S. Dana. Here the crystals are elongated combinations of the octahedron and dodecahedron extended along the different cube-axes and grouped together in a "dendritic" or tree-like form. Dendritic growths — familiar in the frost patterns on window panes — are more usually due to the regular conjunction known as "twinning," described below in Article 3.

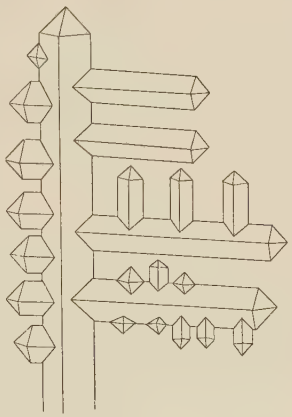


Fig. 225.—Copper.

2. **Regular Conjunction of Crystals which are not Parallel nor Twinned.**—If in a regular growth, whether of the same or of different minerals, the crystals are not completely parallel, they are partially so. In this case two crystals may be so united that (1) a face of one is parallel to a face of the other; that (2) an edge of one is parallel to an edge of the other; or that (3) a face and one of its edges on one crystal are parallel respectively to a face and an edge of the other.

Thus (1) prisms of bournonite terminated by the basal plane are sometimes grouped together so that their terminations all fall into a single plane; (2) prisms of quartz from Switzerland are sometimes so united as to form a twisted or spiral group in which all the edges between (100) and $(2\bar{1}\bar{1})$ are parallel; (3) crystals of the orthorhombic mineral staurolite sometimes are affixed to a crystal of the anorthic cyanite in such a way that the brachypinakoid $b(010)$ of the staurolite is parallel to the face A(100) of the cyanite, and the prism-edges of the two minerals are at the same time parallel (Fig. 226). Again, prisms of rutile (tetragonal)

Fig. 226.—Staurolite on Cyanite.

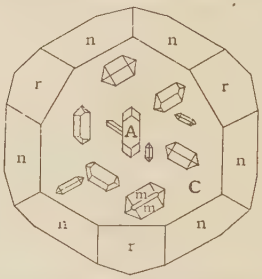


Fig. 227.—Rutile on Hæmatite.

are found attached to plates of hæmatite (hexagonal) in such a position that each rutile crystal lies with a face of {100} upon the basal plane of the hæmatite, and has its prism-edges parallel to the edges of one of the zones $[Cna] = [111, 3\bar{1}1, 1\bar{1}0]$ of the hæmatite (Fig. 227).

The third mode of grouping is sometimes found not only between crystals of different minerals, but between crystals of the same mineral. An instance is afforded by hydrargillite, which crystallises in apparently hexagonal plates. These belong in reality to the monoclinic system and are a combination of C{001}, m{110}, A{100}; on specimens from Langesundfjord two such crystals are sometimes so united that they have their basal planes C_1 C_2 parallel, and also the edge C_1 m_1 of the one parallel to the edge C_2 A_2 of the other (Fig. 228). In this instance the parallel planes on the two crystals are similar, but the parallel edges are different: such a growth is a transition towards the regular conjunction to be presently described as "twinning," in which both the parallel edges and the parallel faces are similar.

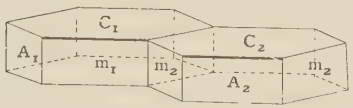


Fig. 228.—Hydrargillite.

The regular deposition upon the faces of a mineral of minute subindividuals belonging to a different species sometimes gives rise to drusiness. Thus tetrahedrite is very commonly covered with a drusy crust of crystalline chalcopyrite, due in all probability to a surface-decomposition of the tetrahedrite. The well-known specimens from Herodsfoot Mine near Liskeard in Cornwall owe their beautiful colour to a tarnished crust of chalcopyrite, which also exhibits the peculiar sheen mentioned above owing to the regular arrangement of the minute crystals.

3. **Twinning.**—Among regular groups of crystals of the same mineral species are found crystals resembling Figs. 230 and 231. Here, if X is an anorthic crystal in which no two faces are at right angles (as in Fig. 229), then X_1 may be derived from X by reflection over the horizontal plane; and X_2 may be derived from X (as regards its orientation) by a rotation of 180° about the front horizontal edge. In other words, if X_1 be reflected over the horizontal plane, or if X_2 receive a half-turn about the horizontal edge, it is brought into a position parallel with X. In Fig. 230 the front faces make an angle with one another: in Fig. 231 they fall into one plane.

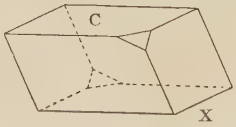


Fig. 229.

In Fig. 230 a face C of one crystal is parallel to a similar face of the other, and *all* the corresponding edges of these faces are parallel.

In Fig. 231 an edge (zone-axis) of one crystal is parallel to a similar edge of the other, and *all* the faces belonging to this zone are also parallel on the two crystals.

Regular groups which fulfil either of these two conditions are known as "twin-crystals."

In Fig. 230 the crystals are said to be twinned about a face, and the plane of reflection is called the "twin-plane": in Fig. 231 the crystals

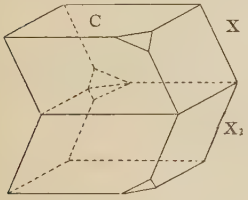


Fig. 230.—Twin-plane.

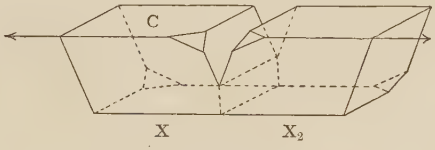


Fig. 231.—Twin-axis.

are said to be twinned about an edge, and the axis of rotation is called the "twin-axis." [1]

In the case of a centro-symmetrical crystal, such as Fig. 229, the relative orientation of the two individuals of Fig. 230 might also be obtained by placing them in parallel position, one on the other, and rotating one through 180° in the plane of the horizontal face which is common to both, *i.e.* giving a half-turn to one crystal while keeping the horizontal faces in contact. In crystals which have no centre of symmetry, however, the results of reflection and rotation will not usually be identical. Thus,

[1] It was formerly the custom to describe twins as due to "hemitropy," or rotation through 180°, about an axis, called the twin-axis, whether a possible edge or not, and to call the plane perpendicular to this the twin-plane, whether it was a possible face or not. Since, however, two enantiomorphous crystals, such as a right- and a left-handed crystal of quartz, are sometimes twinned together so that they are symmetrical about a plane parallel to one of their possible faces (*viz.*, in quartz, the plane truncating a prism-edge), as in Fig. 246, it is clearly impossible to describe all twins as due to hemitropy, since a right-handed crystal cannot be placed parallel to a left-handed one, or obtained from a left-handed one by rotation, any more than a right hand can be placed parallel to a left hand,

in the case of chalcopyrite, which belongs to the di-tetragonal alternating class, thetwins shown in Fig. 232 (*i.e.* of type (2), p. 388) can only be described as due to reflection in a twin-plane parallel to a face of the pyramid $\{101\}$. The twins of type (1), shown in Fig. 233, on the other hand, can only be described as due to rotation in the plane of the face $(11\bar{1})$, and not to reflection in this plane, since the faces opposite to one another on either side of the plane are not similar but belong to two different forms, *o* and ω, which differ in their surface-characters, *o* being frequently dull while ω is bright. In such cases the plane of rotation is sometimes called the twin-plane, and the line perpendicular to it the twin-axis. The former is parallel to a possible face of the crystal, but the latter is not necessarily parallel to a possible edge, and if these terms are retained, care must be taken to explain the sense in which they are used. Twins like the above, in which the twin-axis is not parallel to a possible edge, are, however, not common.

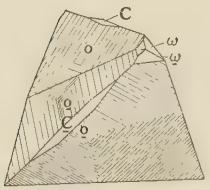


Fig. 232.—Chalcopyrite: Reflection-twin.

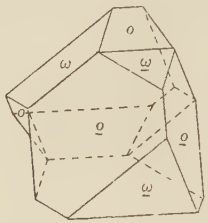


Fig. 233.—Chalcopyrite: Rotation-twin.

Twin-crystals which are explainable as due to hemitropy, either in a plane which is a possible face of the crystal, or about an axis parallel to a possible edge, may be called "rotation-twins." Those which involve reflection in the twin-plane may be called "reflection-twins."

Many twin-crystals may equally well be described in more than one way. Thus the twin of gypsum shown in Fig. 234 may be described as formed of two crystals, Fig. 235, twinned by reflection in the ortho-pinakoid, which would truncate the edge *mm*, or by rotation about the axis Z which is parallel to this edge, or again, by rotation in the plane of the ortho-pinakoid.

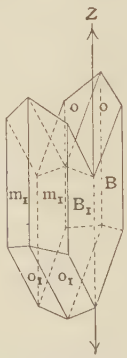


Fig. 234.—Gypsum: Twin-crystal.

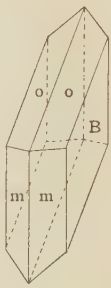


Fig. 235.—Gypsum.

The surface of union may either be a plane, or may be quite irregular. If a plane, it is called the "plane of composition."

The twin may either consist of two crystals placed side by side, as in Fig. 234, when it is called a "juxtaposition-twin"; or the two individuals may pass more or less completely through each other, when it is called an "interpenetration-twin." In the latter case there is usually no plane of composition.

Fig. 236 represents an interpenetration-twin of the orthorhombic mineral staurolite, which received its name from these cruciform growths. Each of the two individuals is here a combination of basal pinakoid {001}, brachy-pinakoid {010}, and prism {110}; the twin-plane is a face of the prism {032} (*cf.* Fig. 703). This face makes an angle of 45° 41′ with the basal plane, so that the twin-crystal is very nearly a right-angled cross.

Fig. 237 represents an interpenetration-twin of two cubes of fluor, the twin-axis being the cube-diagonal (or dodecahedron-edge) OO which

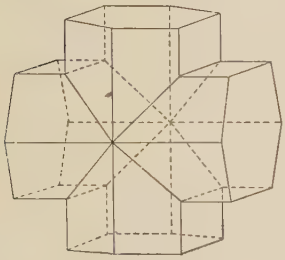


Fig. 236.—Staurolite.

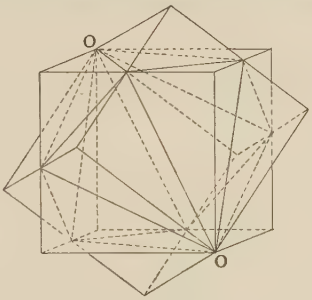


Fig. 237.—Interpenetration of Two Cubes.

is common to them. Fig. 238 is an interpenetration-twin of two octahedra united according to the same law, O being the twin-axis. These individuals might also (though less naturally) be described as united by twinning upon the octahedron-plane, to which that axis is perpendicular. Fig. 239 represents a juxtaposition-twin of octahedra in which the individuals are

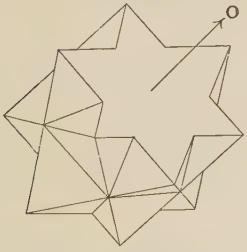


Fig. 238.—Interpenetration of Two Octahedra.

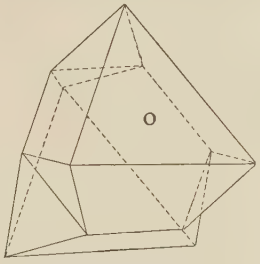


Fig. 239.—Juxtaposition of Two Octahedra; Spinel Twin.

related to each other in the same way, but here union takes place along the octahedron-face, and the crystals are best described as twinned upon that plane. This conjunction is so typical of spinel that it is often called the "spinel twin."

The plane of composition, if any, is generally parallel to the twin-plane, as in Figs. 234 and 239, or it may be parallel to the twin-axis. In this case it is sometimes parallel to a possible face, as in mica (p. 531), or not parallel to any face, as in the twins of pericline described on p. 521.

Most twin-crystals, as in the above figures, betray their nature by

having "re-entrant" angles (*i.e.* angles facing inwards, like m_1m_2, Fig. 228, as contrasted with the "salient" angles of a single crystal, which always face outwards, like m_2A_2); these give rise to notched, jagged, heart-shaped, knee-shaped, or arrow-headed forms very different from those of simple crystals; hence the terms "geniculated" and "macled," which are synonymous with "twinned." The French term *macle* is used by many authors instead of "twin."

Twins which are completely interpenetrant are sometimes grown together in such a way as to be entirely devoid of re-entrant angles, so that to the eye they may appear simple crystals; the twin junction can then only be traced as a fine line traversing the crystal or by the different characters of the faces on either side of the junction. This is very strikingly exemplified by the interpenetration-twins of quartz described on p. 424, where each pyramid-face is dull in one part and bright in another, the dull part belonging to the face z of one crystal and the bright part to the face R of its neighbour. (See also Article 5, below.)

It is evident that an axis of *even* (*i.e.* digonal, tetragonal, or hexagonal) symmetry in a crystal cannot play the part of a twin-axis, for hemitropy about it would restore the crystal to its original aspect and would result in a parallel growth; neither, for the same reason, can any plane of symmetry in a crystal be the twin-plane in a reflection-twin.

4. **Twinning and Structure.**—It must be remembered that rotation about an axis and reflection over a plane only afford a convenient geometrical description of twin-crystals and do not represent any process actually taking place during the growth of the crystal.

The probable explanation of twinning is that crystals consist of material arranged in straight lines and planes to form a regular structure (see p. 273), and that this structure can continue to grow when the arrangement of the material is reversed with respect to some of these planes or lines. In other words, adjacent parts can fit together either in parallel or in reversed (or twin-) position.

In the same way the regular growth of two different minerals, described above, is probably due to the fact that along certain planes their structures are similar and can fit together. (Compare the regular growth of sodium nitrate on calcite, p. 266.)

5. **Supplementary Twinning.**—It will be observed that the effect of twinning is to introduce, into the composite crystal, planes or axes of symmetry which neither of the individuals possesses. A very common mode of twinning is that in which a crystal belonging to one class is twinned about a plane or an axis which is a plane or an axis of symmetry in another class of the same system. The introduction of the new element of symmetry in such cases may cause the twin-crystal to possess the external symmetry of the holosymmetric class.

Thus the upper hemimorphite crystal of Fig. 240, reflected over a plane parallel to the base C, becomes the lower crystal; if these two are united along the twin-plane, as in Fig. 241, the lower crystal supplies the faces t_1 of the supplementary dome $\{30\bar{1}\}$, which would be required to convert the dome $t\{301\}$ into a prism of the holosymmetric class. When

there is a re-entrant angle, as in Fig. 241, the crystal is easily seen to be a twin ; but when the two individuals unite as in Fig. 242, they present the aspect of a single individual in which, moreover, the two ends of the

Fig. 240.

Fig. 241.

Fig. 242.

Supplementary Twinning of Hemimorphite.

crystal cannot be distinguished, for they are actually bounded by faces of the same form. Such twins may be called " supplementary " twins.

Well-known examples of supplementary twinning are the interpenetrating pyritohedra of iron pyrites (Fig. 243) found at Minden in Prussia, and the interpenetrating tetrahedra of diamond (Fig. 244).

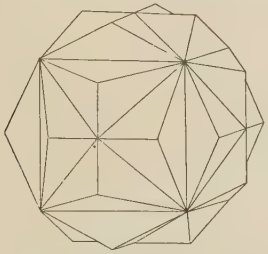


Fig. 243.—Supplementary Twin of Pyritohedra.

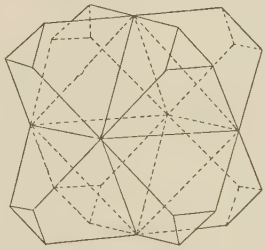


Fig. 244.—Supplementary Twin of Tetrahedra.

The faces of Fig. 243 make up the four-faced cube {210} of the holosymmetric class, and the supplementary tetrahedra of Fig. 244 make up the octahedron ; for a projection of Fig. 243 would contain all the poles corresponding to the faces of Fig. 27, and a projection of Fig. 244 would contain all the octahedron-poles.

The individuals forming a supplementary twin may be either juxtaposed or interpenetrating; in some cases the twin may have the complete appearance of a holosymmetric crystal without re-entrant angles.

Supplementary twins may be either rotational or reflectional, for the two supplementary forms, which have similar indices and together make up a single form of the holosymmetric class, may be related to each other by repetition about either an axis or a plane. Among the reflection-twins the following remarkable case is especially noteworthy.

When a crystal belongs to a class which possesses neither plane of symmetry nor centre of symmetry its reflection in a mirror is, as was explained on p. 54, a different figure, just as the reflection of a right hand is a left hand. With such enantiomorphous crystals, therefore, a reflection-twin is a union of a right-handed with a left-handed crystal.

The most characteristic examples of this sort of twinning are the so-called " Brazilian " twins of quartz (Fig. 246), which consist of a right-

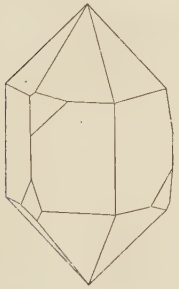


Fig. 245.—Left-handed Quartz.

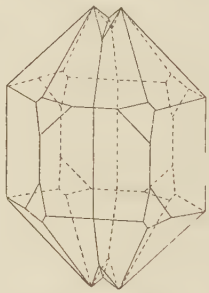


Fig. 246.—Brazilian Twin.

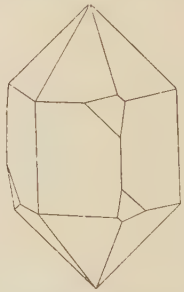


Fig. 247.—Right-handed Quartz.

handed and left-handed crystal united sometimes along the plane of twinning (Fig. 246), but more usually by irregular interpenetration (Fig. 564).

When the supplementary crystals are enantiomorphous the twins cannot be described as merely rotational, since no hemitropy can bring a right-handed crystal (of quartz, for example) into complete parallelism with a left-handed crystal. The present case may be described either as one of twinning about the prism-plane $(10\bar{1})$, or as one of " alternating twinning," due to hemitropy about the vertical axis combined with reflection over the horizontal plane (see p. 424).

6. **Repeated Twinning.**—A very common mode of twinning among minerals is that in which two crystals are twinned together, and then a third crystal is twinned according to the same law upon one of them, and then perhaps a fourth is twinned upon the third, and so on, *e.g.* in aragonite (Figs. 248-250).

This twin-grouping may take place in two ways :

(1) The twin-plane for individuals II and III, though belonging to the same form as that for II and I, may be a different face of the form. This repetition with inclined twin-planes leads to a cyclical grouping,

as in Fig. 249, where the prism-face m_1 about which II is related to I is not parallel to the prism-face m_3 about which it is related to III. Sometimes the repetition even leads to a completely closed chain of individuals, as in the crystal of rutile shown in Fig. 546.

Fig. 248.—Aragonite Twin.

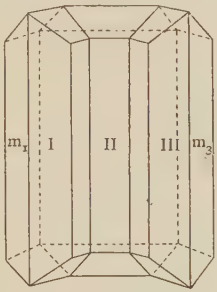


Fig. 249.—Inclined twin-planes.

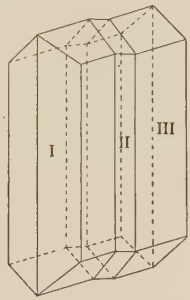


Fig. 250.—Parallel twin-planes.

(2) The twin-plane for II and III may be parallel to that for II and I, as in Fig. 250.

The same applies to the twin-axis in a rotation-twin.

Now it is evident that two successive half-turns about the same line are equivalent to a whole turn, and restore the crystal to its original position, and that two successive reflections about the same plane have the same effect. In case (2), therefore, III will be parallel to I, and II will appear to be interposed in twin-position between two portions of the same crystal (Fig. 250).

If twinning upon a pinakoid form be repeated, it is clear that the second mode of grouping is the only one possible, for the form does not comprise any inclined faces.

The repeated twinning of acicular crystals with inclined twin-planes may give rise to a regular reticulated grouping, as in the rutile from Tavetsch, in Switzerland, which is known by the name "sagenite" from σαγήνη, a net (Fig. 251). Acicular tetragonal crystals are here twinned about faces of the pyramid {011} as twin-plane (*cf.* p. 415).

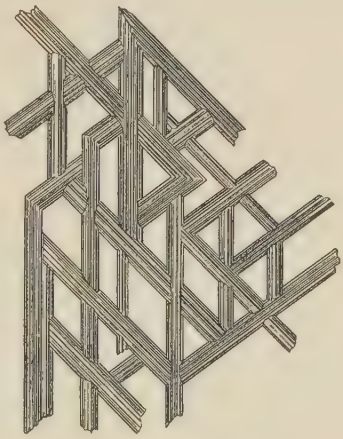


Fig. 251.—Reticulated Twinning of Rutile.

Twin-Lamellæ.—Juxtaposed twin-crystals show a curious tendency to become tabular parallel to the plane of twinning.

This is often exhibited in a remarkable manner by twins which are repeated with parallel twin-planes. Thus the interposed crystal II in Fig. 250 may be reduced to the thickness of a mere plate or twin-lamella.

When the twinning is repeated a number of times with parallel twin-planes, as in the albite of Fig. 253, which exhibits merely a repetition of the twinning of Fig. 252, and the lamellæ are sufficiently thin, the crystal may appear to be a single individual traversed by a series of fine lines, the so-called "twin-striæ," parallel to the plane of twinning. Fig. 254

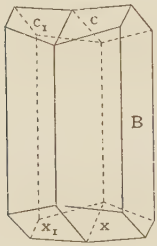


Fig. 252.—Albite Twin.

Fig. 253.—Twin Lamellæ.

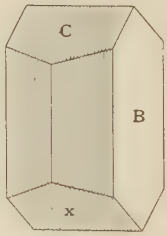


Fig. 254.—Twin Striations.

represents a crystal of albite whose basal pinakoid C, prism-faces, and dome $x\{10\bar{1}\}$ are traversed by twin-striæ all parallel to the pinakoid B. The structure of Fig. 254, if magnified, would present the appearance of Fig. 253. This is known as "polysynthetic" twinning. In albite the twin-plane is B(010), which, since the mineral is anorthic, is not perpendicular to C or to x.

7. **Mimetic Twinning and Pseudo-symmetry.**—In the supplementary twins described above, the planes and axes of twinning would be planes and axes of actual symmetry in some other class of the system to which the crystals belong, and the faces of each crystal, after twinning, occupy the positions of possible faces on its neighbour and would have rational indices if referred to its axes. The two individuals, if without re-entrant angles, may then appear to constitute a single crystal. The result of such twinning is therefore apparently to invest the crystal with a higher degree of symmetry than it really possesses, and to transfer it from one class to a *class* of higher symmetry within the same system.

Another and similar result which may be brought about by twinning is that in which a crystal actually appears to belong to another *system* of higher symmetry than its own. In most systems are to be found certain minerals which approximate very closely to the geometrical symmetry of a more symmetrical system.

Thus, in the anorthic crystals of albite, Fig. 252, the angle BC is about $86\frac{1}{2}^\circ$, or only $3\frac{1}{2}^\circ$ from the right angle which would correspond to monoclinic symmetry. The twin-plane is a plane of symmetry to the twin, and hence in a polysynthetic crystal, like Fig. 254, in which the lamellæ are very thin, the crystal may be scarcely distinguishable from one of the monoclinic system (*cf.* p. 519). Again, an orthorhombic crystal, whose horizontal axes are very nearly equal, will approximate to the geometrical symmetry of a tetragonal crystal, since it will have a prism-angle of very nearly 90°; in such a crystal the vertical axis will be very nearly an axis of fourfold instead of one of twofold symmetry, and planes

parallel to the faces of the prism {110} will be very nearly planes of symmetry (Fig. 255). Such a crystal is said to be "pseudo-tetragonal," or (in the general case) "pseudo-symmetric." Twinning about the prism-faces would have the effect of making the crystal still more nearly tetragonal, since it would make these faces actual planes of symmetry in the twin, and would cause the faces of the different forms to be so repeated as to satisfy the symmetry of the tetragonal system; a pseudo-tetragonal crystal so twinned by interpenetration might be almost indistinguishable from a tetragonal crystal. In this way a crystal may simulate the symmetry of a higher system; such twinning is called "mimetic," or imitative, and crystals so twinned are called "mimetic twins." The term pseudo-symmetric (pseudo-cubic, etc.) is also commonly applied to such twinned groups, especially when the imitation is so close that the true symmetry cannot readily be determined (as in leucite, p. 507).

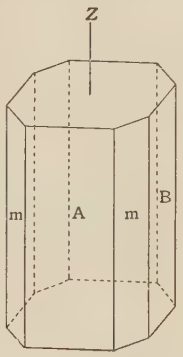


Fig. 255.—Pseudo-tetragonal Axis.

A familiar example is afforded by the orthorhombic mineral aragonite. The prism-angle in this mineral is near 60° (actually 63° 48′); consequently a combination of the prism {110} with the brachy-pinakoid {010} is nearly a hexagonal prism; and planes parallel to the prism-faces are planes of pseudo-symmetry; these are also the common planes of twinning, as shown in Fig. 249.

If each face of the prism-form becomes a twin-plane, the triplet so formed will have two planes of pseudo-symmetry inclined nearly at 60° to each other and to the plane of symmetry of the first crystal, and will approximate even more closely than the simple crystal, or the twin, to the symmetry of the hexagonal

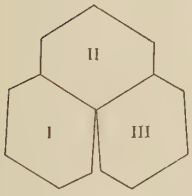


Fig. 256.

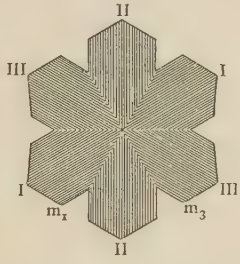


Fig. 257.

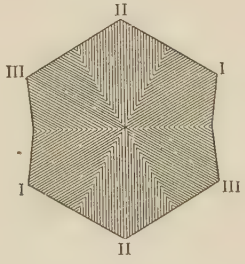


Fig. 258.

Pseudo-hexagonal Triplets of Aragonite.

system; three individuals so twinned will present almost exactly the aspect of a hexagonal prism.

Since the prism-angle is not quite 60° the faces of I and III do not quite fit together (Fig. 256) and these two crystals are not relatively in twin-position.

More frequently the crystals forming a mimetic twin-group are not juxtaposed but interpenetrant, and in such cases the pseudo-symmetry is even more complete.

Thus in the interpenetrant triplet of aragonite (Fig. 257), m_1 is the twin-plane for I and II, m_3 that for II and III.

The crystals may completely interpenetrate, as in Fig. 258, and may be almost indistinguishable from a simple hexagonal crystal. Generally, however, striations on the basal pinakoid which, in each individual, run parallel to the brachy-pinakoid, render it possible to distinguish the various individuals of the group, and faces of III and I form a re-entrant angle.

A remarkable example of twinning, combined with the regular conjunction of one mineral with another, is shown in Fig. 259, which represents a specimen from Brilon in Westphalia, described by Trechmann. The cube is iron pyrites; the other crystals are twins of marcasite (the orthorhombic modification of iron disulphide); they are combinations of prisms {101} and {104}, terminated by the prism {110}, each twinned on a face of {110}, and each cube-face of the pyrites bears a marcasite twin having its twin-plane perpendicular to the cube-face and parallel to the striations upon it.

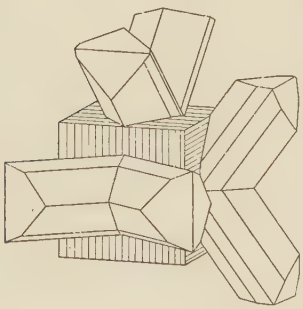


Fig. 259.—Marcasite Twins on Pyrites.

8. **Secondary Twinning.** — It was discovered by Reusch and Baumhauer that when the blade of a knife is pressed into a cleavage-rhombohedron of calcite across one of the terminal edges (at *b*), a slight sideward pressure being at the same time given to the blade towards the summit of the rhombohedron, the following remarkable effect is produced: as the knife enters the crystal, successive layers, all parallel to the plane *cde*, which would truncate the rhombohedron edge, glide along each other; this gliding takes place exactly so far that a portion of the crystal extending to the depth cut by the knife takes up a new position and constitutes a new crystal twinned upon the original rhombohedron by reflection over *cde*, the face (011). This is shown in Figs. 260, 261, where *a'b'cde* is the position adopted by the portion *abcde* of the crystal between the knife and the summit *a*.

The plane (011) along which this gliding takes place is called a "glide-plane," and it becomes after the operation a plane of "secondary" twinning, as contrasted with ordinary twinning which has taken place during the growth of a crystal.

It will be observed that the summit of the crystal was at *a* and is now at *b'*, and the direction *ba* is reversed in *a'b'*, the obtuse angle *a* being converted into an acute angle *a'*.

A complete twin of this sort—such as is sometimes found in Nature as an ordinary twin—is shown in Fig. 262.

Glide-planes have now been observed in many minerals; in most

cases the crystals split easily along planes where gliding has taken place, and the glide-planes are consequently marked by a " parting " (see p. 314).

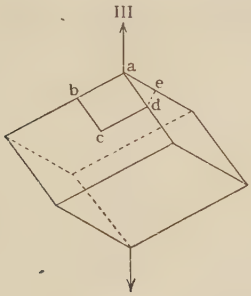


Fig. 260.

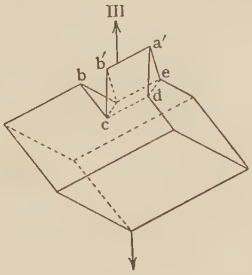


Fig. 261.

Baumhauer's Experiment.

Glide-planes, giving rise to a parting, are also sometimes observed in directions which by virtue of the symmetry cannot be planes of

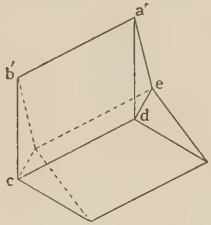


Fig. 262.—Calcite twinned on (011).

twinning, *e.g.* in stibnite parallel to the face (001), which in an orthorhombic crystal is a plane of symmetry (see p. 100).

CHAPTER III

VICINAL FACES

1. **Vicinal Faces.**—It has been stated above that the faces of a crystal are such as possess simple rational indices. But many crystals have bright plane surfaces which cannot be referred to simple indices; these are by no means to be ignored or ascribed to irregularity of growth; they are symmetrical in accordance with the symmetry of the crystal and replace the simple forms which would have low indices; thus, for example, cubes of fluor-spar are generally found, when closely examined, to be in reality four-faced cubes; each apparent cube-face consists of a very flat square pyramid nearly coincident with the cube (Fig. 264). The vicinal faces are of considerable importance in determining the true symmetry of a crystal, for they generally belong, not to the simplest possible forms, which are perpendicular to the planes and axes of symmetry, but to some more complex form capable of indicating the class to which the crystal belongs. When they replace a face which is perpendicular to an axis or a plane of symmetry they can be easily detected by virtue of their repetition; thus a vicinal form replacing the cube in the holosymmetric class must consist of a flat four-faced (Fig. 264) or eight-faced pyramid: one replacing the octahedron must consist of a three-faced (Fig. 269) or six-faced pyramid; the edges between the vicinal planes, and their slight salient angles, can generally be observed though the faces be inclined to one another at very small angles, not exceeding a few minutes.

The vicinal faces of a single crystal must not be confused with the faces which are often met with on twinned *pseudo-symmetric* crystals, where the simple forms belonging to the different constituent crystals meet at very small angles (*cf.* p. 207).

Thus an apparent cube may in reality consist of twelve monoclinic individuals, each having the form of the wedge OABCD, so united that their apices meet in O, the centre of the cube (Fig. 263). If the faces CBD, ABD are respectively the basal pinakoid {001} and the orthopinakoid {100} of the monoclinic individual, the angle between them may be slightly less than 90°; the four faces, such as ABD, which constitute an apparent cube-face will in this case not fall exactly into a plane but will constitute a low four-sided pyramid.

In other cases a similar figure may be due, as in fluor, to vicinal faces

belonging to a four-faced cube (Fig. 264), which replace all the faces of a *single* cube; but whereas the pseudo-symmetric crystals will have a constant angle over the cube-edges, namely the angle belonging to the monoclinic individuals, the vicinal faces of the single cube may belong to different forms in different crystals of the mineral and vary from one

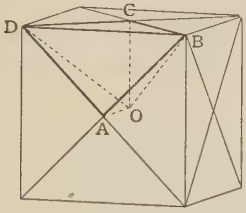


Fig. 263.—Pseudo-symmetric Cube.

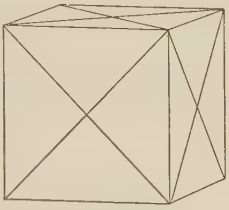


Fig. 264.—Vicinal Faces replacing Cube.

crystal to another. It may conceivably happen that the faces in a pseudo-symmetric crystal are also themselves vicinal faces; the distinction will then be more difficult.

Vicinal faces are very often developed in interpenetrant twin-crystals where one individual emerges through the other. One of the most conspicuous and common examples of this is in fluor-spar, whose crystals are usually the interpenetrant cubes of Fig. 265; in these it will generally be found that the cube-faces through which a corner of the interpenetrating crystal protrudes are replaced by the facets of a flat four-faced cube, as indicated by the shading (*cf.* Fig. 494).

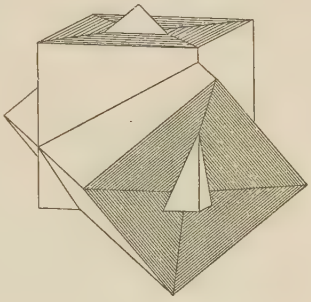


Fig. 265.—Fluor-spar.

Experiments upon crystals grown in the laboratory show that vicinal faces vary during the growth of the crystal—at one moment having one set of indices, and at another moment another; they vary possibly with the concentration of the solution or the rate at which the crystal is growing.

The crystals of natural minerals, which grow, doubtless, under very variable conditions, constantly exhibit vicinal faces; these are very near to the faces of simple forms, and therefore possess very high indices. Their interest and importance consist in the fact that, whatever be their indices, the number of the facets corresponds to the symmetry of the crystal, and they are therefore most valuable aids in determining the class to which it belongs. One way in which this property is employed is the following.

2. **Light-Figures.**—It was noticed by Brewster that when a distant source of light, for example a candle flame, is observed by reflection in a crystal face held close to the eye, the image may be, not sharply defined, but blurred in such a way as to give a curiously regular geometrical

star. Further, that the symmetry of this star is precisely the symmetry of the reflecting face.

It is easy to understand from what has been said above that such images, to which Brewster gave the name of "light-figures," will be produced by vicinal faces.

A perfectly plane reflecting surface will give a single clear image of a small circular spot of light, but a cube-face such as that of fluor, which consists of four vicinal faces, as in Fig. 264, will give four such images which are extremely close to each other, since the four reflecting surfaces are nearly coincident (Fig. 266). If there are a number of vicinal faces

Fig. 266.

Fig. 267.

Light-Figures from Fluor.

lying in the zones of the four cube-edges, *i.e.* a number of consecutive four-faced cubes $\{hk0\}$, the image will be converted into a hazy four-rayed star (Fig. 267).

The image given by any face of an octahedron of common alum is a three-rayed star, as in Fig. 268. This is due to the fact that each

Fig. 268.—Light-Figure from Face of Alum.

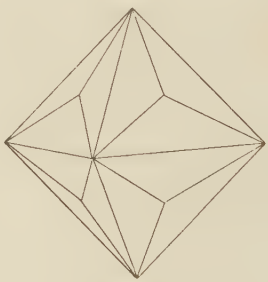


Fig. 269.—Alum.

apparent octahedron-face of alum consists in reality of faces belonging to a number of very flat three-faced octahedra (Fig. 269), whose facets nearly coincide with the octahedron-faces.

The images reflected from a crystal which has been acted upon by a solvent are almost always of this composite nature, for the reason explained below on p. 127.

CHAPTER IV

THE MEASUREMENT OF CRYSTALS

We are now equipped with nearly all that is necessary for the complete description of the "crystalline form" of any mineral. If the angles between the faces of a simple crystal can be measured, their poles may be plotted out on a projection; the planes and axes of symmetry will then reveal themselves, and, according to its symmetry, the crystal can be referred to one of the six systems, and to one or other of the classes within that system, due regard being paid to the physical features of the faces as well as to the angles which they make with one another.

Three faces are chosen as "axial planes," which by their mutual intersections give the directions of the axes; in the anorthic system any three faces may be selected; in the other systems they must be chosen in accordance with the symmetry, as has been explained above on p. 41. A fourth face which intersects all three axes is then chosen as "parametral plane" to determine the lengths of the axes; or two faces, each of which cuts two axes and is parallel to the third, may be used for the same purpose. The lengths and inclinations of the axes are then calculated and the indices of the remaining faces of the crystal are determined by their zonal relations.

But to make any such description possible it is necessary to measure the angles between the faces; this is done by means of the instrument known as the "goniometer." Of this instrument there are two sorts: (1) the contact-goniometer, and (2) the reflecting goniometer. The former was the contrivance used by Romé de l'Isle and Haüy, the French crystallographers who first measured crystals with accuracy, and is still employed for large dull crystals whose faces are not smooth enough to yield reflections of a distant object; but for all accurate measurements it has been supplanted by the reflecting goniometer invented by Wollaston in 1809.

1. **The Contact-Goniometer.**—The contact-goniometer consists simply of two straight steel bars hinged together by a pivot, and fitted to a graduated semicircular arc whose centre coincides with that of the pivot (Fig. 270).

To measure the angle between two faces A and B, the arms are adjusted until one is in contact with the face A, and the other with the face B; to ensure close contact the crystal is held up to the light and viewed along the edge between A and B, and the arms are moved about

the pivot until no light passes between them and the faces, care being taken that the plane containing the arms is perpendicular to the edge. One arm is usually fixed so as to coincide with the zero division on the scale.

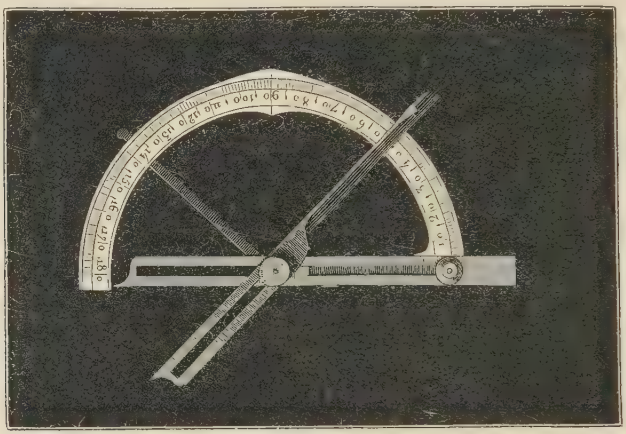


Fig. 270.—Contact-Goniometer.[1]

Sometimes the two arms and their pivot are so made that they can be removed from the scale and adjusted by themselves, and then replaced upon the scale in order to determine the angle.

2. **The Reflecting Goniometer.**—The reflecting goniometer is an instrument of far greater precision and delicacy, and is universally employed when small crystals with bright faces are available; its principle is as follows:

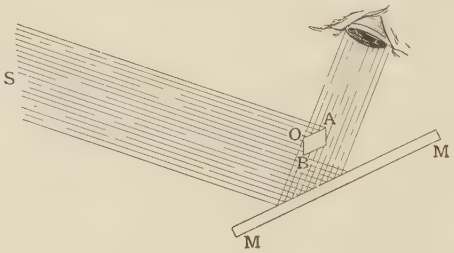


Fig. 271.—Principle of the Reflecting Goniometer.

Let M (Fig. 271) be a fixed mirror in which is viewed the image of a bright signal, such as a horizontal slit cut in a window-shutter, placed beyond S, at a distance of 20 feet or more from the mirror.

Let OA, OB be two bright faces of a small crystal, and let their edge O be parallel to the mirror. The crystal is first so placed that the image

[1] Fig. 270 is reproduced from a photograph of an instrument, exactly like Haüy's own goniometer, presented to Professor Buckland by the Duke of Buckingham in 1824, and now in the Oxford Museum.

of the signal as seen by reflection from OA exactly coincides with the image reflected in M; this is easily effected if the crystal is a small one, since rays producing the two images can then enter the eye at the same time. The crystal is then turned about its edge O until the image of the signal seen in OB exactly coincides with the image reflected in M; and the angle α through which it has been turned is registered. Let a, b be normals to the two crystal faces; it is evident that in the second observation the face OB occupies the exact position which the face OA had in the first observation, hence b has been turned into the position of a, and the angle α must be the

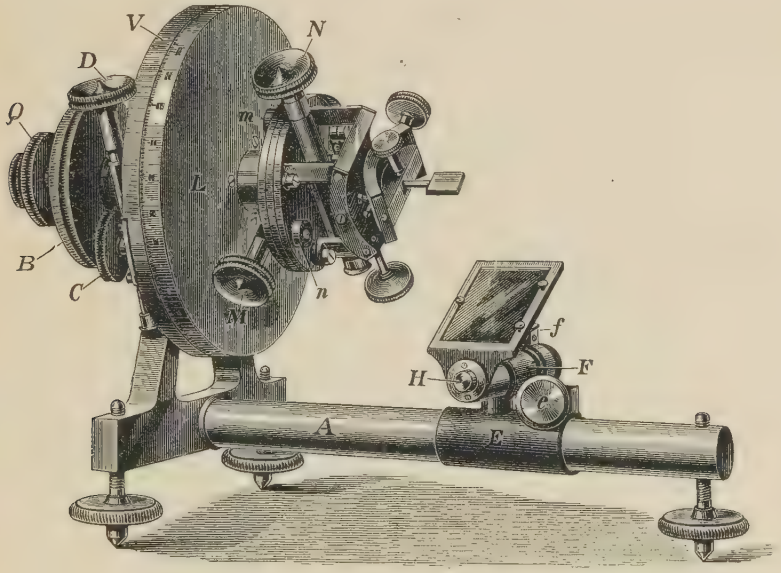


Fig. 272.—Reflecting Goniometer.

angle between the normals a, b (*cf.* Fig. 60). But this is the very angle which is taken in crystallography to measure the inclination of the two faces (see p. 33). The measurement of the normal angle is therefore made directly by means of the reflecting goniometer.

To apply the above principle the necessary requirements are (1) a graduated circle, to the axis of which the crystal is fixed; (2) means for making the edge O parallel with the axis of the circle and for bringing the centre of the crystal to coincide with that axis; (3) means for setting the mirror parallel to the axis.

In the goniometer (Fig. 272), L is the graduated circle, having a scale divided to half degrees, which is turned by the milled head B, and a vernier upon the fixed disc V permits readings to be made accurately to one minute.

The mirror, which is made of black glass, may be fixed at any distance from the circle and at any required inclination by sliding or rotating the

tube E on the bar A. E is clamped by the screw *e*; the mirror, after being adjusted parallel to the axis of the instrument by rotation about the screw H, is clamped by tightening that screw.

The crystal is fastened by a mixture of bees'-wax and pitch to the small brass pin with a flat square head shown above the mirror, projecting from the crystal-holder. The latter is a contrivance for "centreing" the crystal and "adjusting" its edge parallel to the axis; the two screws M and N are used to move the crystal in two directions at right angles until it occupies a central position exactly on the axis, and does not leave its position when the circle is rotated. In front of these are two smaller screws at right angles to each other, which set in motion two cylindrical arcs of which the crystal occupies the centre; these are used to tilt the crystal until its edge is parallel to the axis. After the crystal has in this way been properly centred and adjusted, it rotates about its own centre when the graduated circle is turned, and it is then ready for the measurement of the angle between the two faces which meet in the adjusted edge.

C is a clamp for the circle, and D is the fine-adjustment.

The manner in which the goniometer is actually used is shown in Fig. 273. This figure represents a simple form of the instrument in which the crystal-holder is practically the same as that used by Wollaston in his original goniometer. In place of the cylindrical arcs and tangent screws of Fig. 272 are two pins at right angles to each other, supplied with milled heads by which they can be rotated in their bearings; these pins, to one of which the flat-headed pin carrying the crystal is fixed, constitute two axes at right angles, by means of which the crystal-edge is adjusted parallel to the axis of the disc. The crystal is then centred by means of the slotted L-shaped bracket which carries the adjustment piece; this bracket is shifted upon the goniometer disc until the crystal is on the axis of the instrument, and is then clamped to the disc.

In order to make the image of the signal seen in the crystal exactly coincide with that seen in the mirror, it is convenient to introduce in front of the mirror a small card screen just high enough to intercept the light which falls from the signal upon the mirror, but not that which falls upon the crystal; the screen having been moved sideways until it cuts off half the image of the horizontal signal-slit as seen in the mirror, the crystal is turned until the image seen in its face exactly forms a prolongation of the half-image seen in the mirror. The position of the scale is then read by means of the vernier.

A great advantage of the reflecting goniometer is due to the fact that when once two faces of a crystal have been correctly adjusted, so that during a rotation of the circle the images reflected by these two faces come in succession into their proper position, the axis about which the crystal turns is parallel not only to the edge in which the two faces intersect, but also to the axis of their zone. *All* the faces in the zone must therefore also give correctly adjusted images in succession, and all the angles belonging to that zone can be measured during a single rotation of the divided circle.

Even without making any angular measurements the observer may thus, by a single rotation of the crystal, quickly identify all the faces which belong to a zone.

The examination of a crystal by the reflecting goniometer consists in the adjustment and measurement of one zone after another. In any zone the reading of the scale for each successive face is noted, and the

Fig. 273.—Crystal Measurement.

angle between any two faces is simply the difference between their two readings.

In viewing the images the eye is placed at such distance from the crystal, that it easily takes in at the same time the reflections both from the crystal and the mirror. It must be focussed on the signal and not on the crystal.

Before adjusting a zone it is advisable to mount the crystal upon the wax in such a position that the zone-axis is approximately parallel to the axis of the instrument, and so that a prominent face of the zone is parallel to one of the tangent screws which move the two cylindrical arcs, and perpendicular to the other (or, in Fig. 273, parallel to the smaller

adjusting-pin). This face is first adjusted by the tangent screw to which it is perpendicular (or by turning the smaller adjusting-pin) until the image of the signal seen in it coincides, end for end, with that seen in the mirror. A second face in the zone is next similarly adjusted by the second tangent screw (or the larger adjusting-pin). The graduated circle is then turned back to its original position, and the first face re-adjusted by the first screw. After a few repetitions of this process, both faces, and therefore the whole zone, will be found to be in adjustment.

It is necessary to use a signal situated at a considerable distance from the goniometer, so as to avoid the error due to imperfect centreing of the successive faces of the zone. The greater the distance of the signal the more nearly are the crystal-faces parallel to the mirror when the two images coincide. Where space is limited a very convenient plan is to have for signal a small slit situated at the principal focus of a large lens placed between the slit and the mirror; the rays of light which diverge from the slit and fall upon the lens issue from the lens as parallel rays, and are equivalent to rays from a signal placed at an infinite distance from the instrument. The slit may be illuminated by a lamp placed behind it.

By means of the reflecting goniometer the angles of even the smallest crystal may be measured with great accuracy, provided that its faces are sufficiently smooth and bright to yield reflections of the signal.

The Telescope-Goniometer.—For greater convenience and for more refined work upon good crystals, goniometers are made in which the graduated circle is horizontal and its axis vertical. The signal is a small slit illuminated by a lamp, and is placed at the principal focus of a lens which is situated near to the crystal and renders the rays from the slit parallel; the lens and slit constitute a *collimator*. There is no mirror, the observations being made with a fixed telescope furnished with cross-wires in the eyepiece; each face is adjusted until the centre of the image of the collimator-slit reflected by the face exactly coincides with the cross-wires. A convenient form of slit is that shown in Fig. 274, which represents the reflected image of the signal as seen in the field of the telescope and adjusted upon the cross-wires.

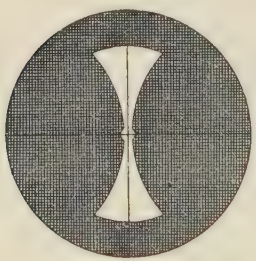


Fig. 274.—The Signal.

By means of an auxiliary lens placed in front of the object-glass the telescope may be converted at will into a microscope, so that the crystal may be examined and adjusted.

In Fig. 275 the left-hand tube is the collimator and the right-hand tube the observing telescope; of the three milled heads at the lower part of the instrument the lowest serves to raise or depress the crystal-holder; the next, to rotate the crystal-holder during adjustment; the upper one, to rotate the graduated disc during measurement.

The scale is read by a small lens shown in the figure.

The telescope is represented with the auxiliary lens placed before the

object-glass for the purpose of viewing the crystal. This lens is carried on an arm hinged to a sliding piece which moves along the telescope. By swinging back the arm another lens is brought in front of the eyepiece; this serves to identify the facet which reflects the image seen in the telescope, for when the lens is close to the eyepiece the image is seen, and if it be withdrawn gradually from the eyepiece the facet becomes visible.

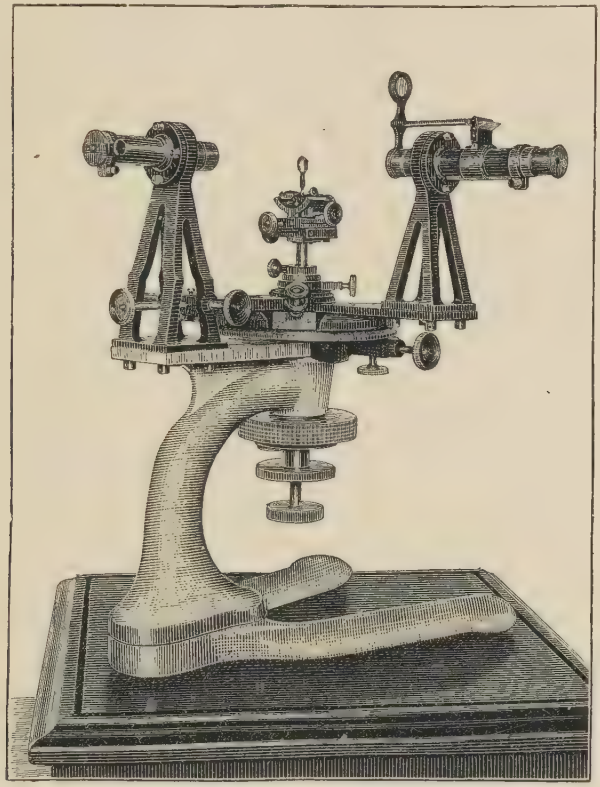


Fig. 275.—The Telescope-Goniometer.

The telescope-goniometer can also be used as a spectrometer, to measure the refractive indices of a mineral by means of a refracting prism (see p. 187).

From what has been said above (p. 110) it is evident that the *symmetry* of the reflected image will often indicate the symmetry of the faces. Vicinal faces, whether produced by the natural growth of the crystal or by subsequent etching, will give multiple images. A face which is perpendicular to an axis of trigonal symmetry will therefore generally give a triradiate star, if a small hole be used as signal; one which is perpendicular to an axis of tetragonal symmetry will give a star-shaped reflection having

four rays. It is therefore of great importance to note the character of the image yielded by each face of a crystal, both as regards its sharpness and its symmetry. In determining the constants of the crystal more importance is to be attached to sharply defined single images than to multiple images or such as are blurred.

CHAPTER V

SOME PHYSICAL PROPERTIES CHARACTERISTIC OF CRYSTALS

1. **On the Relation between Physical Properties and Form.**—From the physical point of view a crystal is very different from the uncrystallised substance, just as a military formation is a very different thing from a crowd of men; the material may be the same, but it is differently arranged. When a crystal is subjected to any physical action the resulting effects depend not only upon the magnitude and nature of the action, but also upon the direction in which it is applied.

The crystal may, for example, be more elastic in one direction than in another; its behaviour will then be different according to the direction in which pressure or flexure is applied; or, again, the action of the crystal upon radiant energy, such as light, may be different according to the direction in which the light is transmitted: the crystal may, for example appear more opaque or more deeply coloured when viewed in one direction than in another; or, again, the crystal when heated may expand unequally in different directions, indicating that its behaviour is different in different directions even when it is uniformly subjected to the same action (*cf.* p. 3). These facts point to a regularity in the arrangement of the particles, owing to which the properties of the crystal are the same along any parallel lines of particles, but are different along other lines of particles inclined to the first. Crystals are then said to be "anisotropic," to distinguish them from "isotropic" substances, such as glass, in which the properties are the same in all directions.

Now the external form of the crystal is doubtless also due to the internal arrangement of the particles, and we have found the external form to be governed by certain simple laws of symmetry, according to which certain faces of the crystal are repeated, and certain directions in the crystal are similar to each other.

It is not surprising, therefore, that the same general laws of symmetry are found to govern the physical characters. This we have already seen to be the case with the cohesion, as indicated by the property of cleavage. When cleavage takes place along any one plane it can also be obtained with equal facility along all the planes belonging to the same "form"; that is to say, the directions of least cohesion are symmetrical directions in the crystal, and are repeated over the planes of symmetry and

round the axes of symmetry. This is equally true of all the physical characters.

All lines in the crystal which are similar in the geometrical sense are also lines along which the physical characters are the same, and the planes and axes of symmetry which have been described are planes and axes of symmetry both for the geometrical and the physical features.

To establish the truth of this extremely important law, many careful measurements have been made of properties which are otherwise of little practical value for the purpose of determining the systems of minerals, or of identifying species; such are the comparative measurements of the elasticity, cohesion, and expansion of crystals; of their conductivity for heat and electricity; of their magnetic properties and dielectric constants; these are for the most part omitted here as belonging more properly to physical crystallography.

One class of characters in particular is of the greatest theoretical importance, and is at the same time so easy of observation that it affords one of the most subtle and yet the most facile means of determining the symmetry of crystals and of identifying species, even when the crystalline form is not available. These are the group of phenomena known as the *optical characters*, which merit a detailed study on the part of every student of mineralogy and will be considered in the next chapter.

Before describing the optical characters we may illustrate the connection between the symmetry of form and structure by a brief reference to certain experiments upon the thermal conductivity, elasticity, cohesion, and some other properties of crystals.

2. **Thermal Conductivity.**—The conductivity of a crystal for heat in a given direction may be determined by measuring the rate of flow of heat along a bar of given dimensions, cut from the crystal in this direction, whose ends are maintained at different temperatures. The variation of this property in different directions may then be represented by drawing lines radiating from a point in all directions, and making their lengths proportional to the conductivity. The ends of these lines will trace out a surface, the "surface of thermal conductivity," whose form will express the conductivity of the crystal. In the most general case this surface is found to be an ellipsoid with three unequal axes (see Fig. 321).

This surface always conforms, in its shape and orientation in the crystal, to any planes or axes of symmetry shown by the crystal form. Thus, in a crystal of the holosymmetric class of the orthorhombic system, the three planes of symmetry of the ellipsoid coincide with those of the form; and in a monoclinic crystal, one of these planes coincides with the single plane of symmetry of the form.

In a crystal of the hexagonal or tetragonal systems, whose symmetry is higher than that of the ellipsoid, the conductivity-surface is a spheroid, or ellipsoid of revolution, so orientated that its axis of revolution coincides with the principal axis of the crystal. In such crystals the conductivity is the same along all lines equally inclined to the principal axis.

In a cubic crystal the surface is spherical, the conductivity being equal in all directions.

The variation of the conductivity of a crystal in different directions may be shown in two ways :

(1) *Senarmont's Method.*—A face of the crystal is coated with a thin film of wax and is warmed by contact with the pointed end of a heated brass rod. The heat travels outwards in all directions from the point of contact by conduction through the crystal, and the wax is melted round the heated point. The outline of the melted portion is an ellipse (or a circle), which may be called the "curve of conductivity" of the face, and corresponds approximately to a section of the conductivity-surface by the plane of the face.

(2) *Röntgen's Method.*—The face is breathed on and then quickly touched with the heated rod.[1] The thin film of moisture is driven off round the point of contact, leaving a dry spot having the form of the conductivity-curve, which can be made permanent by quickly dusting the surface with lycopodium powder, which adheres to the moist part and can be shaken off from the dry space.

With either of these methods the common faces of quartz and cleavage-plates of stibnite or gypsum give well-marked elliptical curves. On a basal section of quartz the curve is a circle.

In stibnite the ellipse has its axes vertical and horizontal, in accordance with the orthorhombic symmetry ; in gypsum its axes lie obliquely.

The variation of conductivity may be readily illustrated with a cleavage-plate of gypsum ($CaSO_4 . 2H_2O$) by allowing the pointed rod to rest upon the surface and heating it with a Bunsen gas flame. The water of crystallisation is then driven off in the heated area and leaves an opaque white spot which has the form of an ellipse, representing approximately the conductivity-curve.

If other faces of the crystal be treated in the same way elliptical outlines will be obtained, which differ in their form on different faces but have the same form, and are symmetrically orientated, on faces which are symmetrical to one another, as shown in Fig. 276.

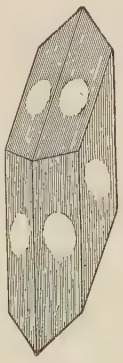


Fig. 276.—Curves of Conductivity of Gypsum.

3. **Elasticity.**—The elasticity (or resistance to stretching or compression) of a substance in any direction is defined as inversely proportional to the elongation produced in a bar of given length and unit sectional area when stretched by a known force, the bar being cut so that its length coincides with the required direction.

Experiments have been made upon crystals to determine the elasticity by the amount of flexure produced in a bar of given dimensions under the action of a given weight. For this purpose a narrow rectangular bar cut out of the crystal in a given direction is supported on two knife-edges, whose distance from each other can be accurately

[1] Or the face may be first touched with the hot rod and then breathed on. The moisture then condenses only on the unheated portion.

measured, and it is then subjected to the action of a weight suspended from a knife-edge which rests upon the slice midway between the supports. The length, breadth, and thickness of the slice having been determined by micrometric measurements, the amount of bending is measured by delicate mechanical or optical means, and from these data the "coefficient of elasticity" may be calculated.

Experiments of this nature have been made upon crystals, and have proved that the elasticity is always the same in directions which are symmetrical to each other with regard to the planes and axes of symmetry.

If lines were drawn in all directions from any point within a crystal, each line representing by its length the elasticity in its own direction, their extremities would form an "elasticity-surface," which would be found to have the same planes of symmetry as the crystal itself. Lines drawn in the same way in one plane, say, upon a crystal-face, would give an "elasticity-curve" characteristic of that face.

Comparative experiments have been made upon calcite and dolomite,

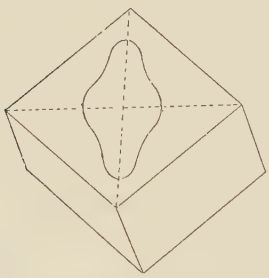


Fig. 277.—Calcite, Elasticity-curve.

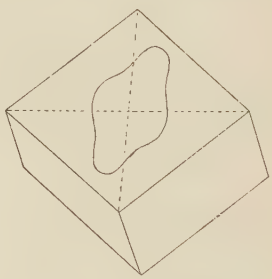


Fig. 278.—Dolomite, Elasticity-curve.

and Figs. 277, 278 represent the elasticity-curves belonging to a rhombohedron-face of each; in the former the curve is symmetrical to the shorter diagonal of the face, and indicates that the crystal has the complete symmetry of the calcite class; but in the latter it has not this plane of symmetry, and indicates that dolomite belongs to the dioptase class, a fact which had been suspected from the distribution of its faces but was difficult of proof on that ground alone.

Where it has only been necessary to compare the elasticity in different directions without actually *measuring* it in any direction, other devices have been employed.

Thus the note produced by a vibrating rod depends mainly upon the elasticity in the direction of the rod. Bars of the same dimensions cut out of rock crystal in different directions have been found to give different notes when fixed at one end and set in vibration; but in this, as in all cases, such bars cut in directions which are similar in the crystal will give the same note because they have the same elasticity.

4. **Cohesion.**—This property has been sufficiently illustrated above by the cleavage of crystals. If there be a cleavage parallel to one face, it

always takes place also, and with equal facility, parallel to all the faces of the form to which that face belongs.

This shows that the plane surfaces of minimum cohesion are parallel throughout the crystal, and are repeated over all its planes and axes of symmetry.

Closely allied to the cleavage, and evidently a result of the different cohesion in different directions, are the so-called "percussion-figures" which are shown by some crystals. If a crystal-face be struck with a sharp point, an indentation is made from which certain lines radiate; these are lines of easy separation in the crystal, and may possibly correspond to imperfect cleavages; but they are sometimes obtainable when cleavages parallel to them cannot be produced, and they then give a further insight into the symmetry.

If a cleavage-plate of mica be laid on a block of wood and struck a sharp blow with a pointed punch a six-rayed star is produced, whose rays determine three directions in the face

Crystals of mica are frequently hexagonal in appearance, but one of the percussion-rays is usually more definite than the other two, and may be easily distinguished from them (Fig. 279).

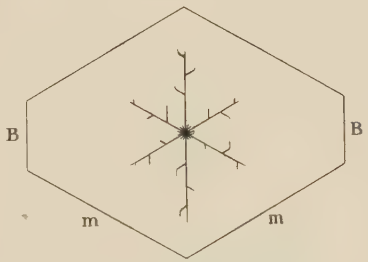


Fig. 279.—Mica, Percussion-figure.

The hexagonal plates are in reality monoclinic, and are a combination of prism (*m*) and clinopinakoid (B) terminated by the basal cleavage; their plane of symmetry must therefore be parallel to one pair of edges of the hexagon. The more definite ray of the percussion-figure (vertical in Fig. 279) indicates the direction of the plane of symmetry.

In the case of mica cracks may also be produced by placing a cleavage-plate upon an elastic surface and pressing upon it with a blunt instrument. These are the so-called "pressure-figures." The cracks are not the same as those of the percussion-figure, but are perpendicular to the edges of the plate of Fig. 279, so forming a second six-rayed star; but this, like the first, is symmetrical only to a plane parallel to B.

Some of the lines of percussion-figures and pressure-figures doubtless correspond to glide-planes, which are not (as was the case with calcite) necessarily also planes of secondary twinning.

5. **Hardness.**—This character, though not capable of absolute measurement, may be compared in different directions upon the same crystal-face, or even upon different crystal-faces, by means of an instrument termed the *sclerometer* (σκληρός, hard).

In the original form of the sclerometer the crystal was fixed upon a small carriage with the experimental face uppermost; upon this rested a lever armed with a diamond point and weighted; the carriage was set in motion by a weight connected with the carriage by a string passing

over a pulley, and the load upon the lever was gradually increased until just sufficient to produce a visible scratch.

The crystal (being mounted upon an adjustable turn-table on its carriage) was then turned through a small angle in its own plane and the process repeated for a new direction. In this way the "hardness" was measured for any number of successive directions in the crystal-face; the least load necessary to produce a visible scratch being taken as a measure of the hardness in each direction.

Now if from any point in a face lines be drawn in different directions representing by their length the hardness along those directions, their extremities will trace out the "curve of hardness" characteristic of that face. This is found, like the elasticity-curve, to be a symmetrical curve having the same planes of symmetry as the crystal. The curves of hardness for the cube- and octahedron-faces, respectively, of fluor-spar are shown in the adjoining figure (Fig. 280). On the cube-face, which is intersected at right angles by four planes of symmetry, the curve has di-tetragonal symmetry; whereas on the octahedron-face, whose normal is an axis of di-trigonal symmetry, the curve possesses di-trigonal symmetry.

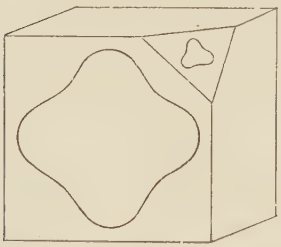


Fig. 280.—Fluor-spar, Curves of Hardness.

It is evidently difficult to estimate with precision the exact weight by which a visible scratch is made.

A more precise method of observation is that of Pfaff, in which the diamond point is weighted with a sufficient constant load, and the crystal is drawn to and fro below it a certain number of times in a given direction. The hardness in that direction is then indicated by the amount of material scratched off the face during the process, and this is measured by the loss of weight experienced by the crystal, which is weighed before and after each such operation. The "hardness" being taken as inversely proportional to the loss of weight, lines are drawn from a point as before, indicating by their length the hardness in each direction; and the curve of hardness obtained by uniting all their extremities is found to possess the geometrical symmetry of the crystal-face upon which the observations are made.

A simple method, by which the "hardness" of different minerals, or of different faces of a crystal, though not that in different directions in the same face, may be readily compared, has been recently described by Holmqvist. This consists in grinding the crystal-face with fine carborundum powder on a plate of quartz. The "hardness" of the crystal, as compared with that of quartz (taken as 1000), is taken as inversely proportional to the weight lost by the crystal as compared with that lost by the quartz.

It is somewhat difficult to say exactly what is meant by "hardness." In all the above experiments the quality estimated is rather "susceptibility to scratching." In some experiments made by Auerbach a small spherical surface was pressed against the crystal and the "hardness" of

the latter determined from the weight required to overcome its elasticity, *i.e.* to develop cracks at the contact, or to produce a permanent impression.

6. **Etched Figures.**—Another extremely important method of investigating the symmetry of a crystal, and one which (like cleavage and susceptibility to scratching) may be regarded as based upon differences of cohesion in different directions, consists in the etching or corrosion of the crystal by a solvent.

When a crystal is acted upon by a solvent, whether water, acid, steam, or a gas, which is capable of attacking it, the first action of the solvent is not only to dissolve away the projecting parts so as to round off the corners and edges, but also (and sometimes even before such action takes place) to attack the faces themselves; the process of solution does not go on uniformly over the whole of each face, but begins at different points and thence proceeds more easily in some directions than in

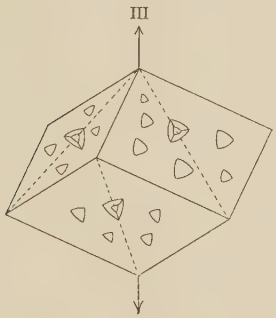


Fig. 281.—Calcite etched with HCl.

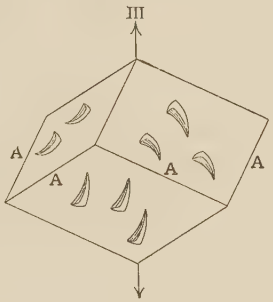


Fig. 282.—Dolomite etched with HCl.

others, with the result that the face becomes covered with regular figures of microscopic size etched upon it by the solvent.

These figures are usually shallow depressions; their sides are minute facets slightly inclined to the face upon which the figures are produced, and are often curved. These little etched faces are in fact vicinal faces, generally belonging to forms different from those to which the crystal-faces belong, and for the most part to forms which are not perpendicular to planes and axes of symmetry, as is so often the case with the natural faces of a crystal. For this reason these etched figures are of the greatest possible value in indicating the true symmetry of a mineral.

For example, a cleavage-rhombohedron of calcite immersed in dilute hydrochloric acid becomes covered with the little pit-marks shown in Fig. 281. These are strictly in accordance with the supposition that the crystal possesses three vertical planes of symmetry; for each little etched figure possesses one line of symmetry parallel to the shorter diagonal of the rhombohedron-face, so indicating that a plane of symmetry intersects that face perpendicularly along this line.

On a cleavage-rhombohedron of dolomite, on the other hand, the etched figures are asymmetric in outline (Fig. 282), indicating that

there is not a plane of symmetry perpendicular to the rhombohedron-face.

In interpreting the etched figures on any crystal it must be borne in mind, not only that the shape of the figure etched upon each face indicates the symmetry of that face, but also that all those faces upon which the same figure is etched must belong to the same form.

Now the figures upon the three upper rhombohedron-faces of Fig. 282 are similar, and are enantiomorphous to those upon the three lower faces. The crystal, therefore, possesses one axis of alternating hexagonal symmetry. Hence, while calcite is di-hexagonal, dolomite is hexagonal and belongs to the dioptase class; this conclusion is fully confirmed by the occurrence of other rhombohedron-faces (like *s* in Fig. 193) which occasionally, though rarely, appear upon natural crystals of dolomite. The ordinary combinations do not enable the mineral to be distin-

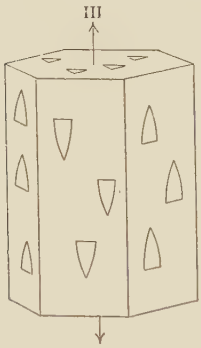


Fig. 283.—Calcite etched with HCl.

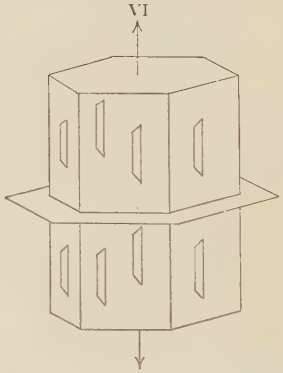


Fig. 284.—Apatite etched with HCl.

guished from one which has the di-hexagonal symmetry of calcite. Reference to Figs. 277 and 278 shows that the evidence of the etched figures is precisely the same as that of the elasticity-figures.

The value of experiments on etching is well illustrated by the case of two minerals which crystallise in hexagonal prisms. A hexagonal prism terminated by the basal pinakoid may belong to almost any class of the hexagonal system. Such a prism of calcite etched with hydrochloric acid gives the figures shown in Fig. 283. The equilateral triangles upon the basal plane show that this face is perpendicular to an axis of trigonal but not of hexagonal symmetry. The similar curved figures upon the several prism-faces show quite clearly—

(1) That the six prism-faces belong to the same form;

(2) That each is perpendicular to a vertical plane of symmetry;

(3) That axes of digonal symmetry emerge through the prism-edges, but not perpendicularly to the prism-faces.

The crystal must therefore belong to the class possessing three planes of symmetry intersecting in an axis of alternating di-hexagonal symmetry, and is the prism $\{2\bar{1}\bar{1}\}$ of Fig. 167. The figures upon adjacent prism-

faces being inverted with regard to each other, each face must be derived from its neighbour by repetition about a hexagonal axis of symmetry combined with reflection over a plane.

A similar prism of apatite etched with hydrochloric acid shows the figures of Fig. 284. Here the figures on each prism-face are similar and not inverted—they can only be obtained from each other by repetition about a vertical axis of hexagonal symmetry. Further, the figures, unlike those of calcite, are similar at their upper and lower ends; hence the crystal also possesses an equatorial plane of symmetry perpendicular to the hexagonal axis, as shown in the figure.

It is customary to distinguish the faces which are sometimes produced by corrosion upon the corners and edges of a crystal as "prerosion faces," while the term "etched faces" is reserved for those minute planes which form the sides of the etched figures.

A closer study of the etched figures upon various minerals shows that they are of two sorts: some faces of the crystal become covered with minute depressions or pits, others with minute elevations or hillocks; the latter are really due to the production of such large and numerous pits that the face is almost completely etched away, and the intervening spaces constitute the hillocks. Those crystal faces, therefore, which are etched into hillocks are precisely the faces which oppose least resistance to the solvent and are most rapidly etched away.

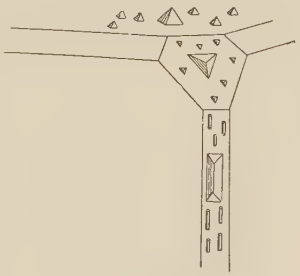


Fig. 285.—The Etching of Magnetite.

The whole process may be described as the production of planes which lie near to, but are not coincident with, certain simple forms, and occupy variable positions in certain simple zones; in other words, they are vicinal planes.

Thus magnetite etched with acids gives triangular pits upon the octahedron-faces, rectangular pits upon the dodecahedron, and square hillocks upon the cube (Fig. 285). All these figures are bounded by minute facets in the zones of the octahedron-edges, for the most part three-faced octahedra. They give the crystal a drusy aspect; and the little facets sometimes reflect simultaneously the light from a distant flame, showing that they belong to the same form though etched on different faces of the crystal.

The etched faces appear to be planes having indices which are rational, although not in general simple. The probability that they do obey the law of rational indices is suggested by the fact that they always lie in certain well-defined zones of the crystal; in this respect they resemble the vicinal faces described on p. 108.

There is yet another method of investigating the action of solvents. A crystal is cut into the form of a sphere and immersed in the solvent; after being subjected to the action for some time the sphere will have altered in shape, and the comparative extent to which corrosion has taken

place in different directions may be ascertained by measurement of the different diameters; or again, a cylinder may be used whose axis is parallel to that of a given zone in the crystal, so that the comparative rates of corrosion in directions perpendicular to the various faces of the zone may be measured by the decrease of different diameters of the cylinder.

In this way it has been proved that those directions along which the greatest corrosion has taken place are nearly perpendicular to the faces upon which etched hillocks are produced, and that those directions along which the least corrosion has taken place are nearly perpendicular to the faces upon which pits are etched; further, that during the corrosion of a sphere certain more or less plane surfaces are developed which are parallel to crystal faces. These planes are generally somewhat rounded, but they are approximately parallel to the little etched faces which form the sides of the pits and hillocks upon an etched crystal.

Both the form of the etched figures and the indices of the etched faces

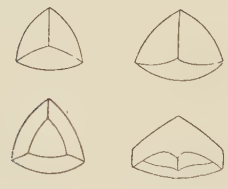


Fig. 286.—Etched Figures on Calcite {100}, obtained (*a*) with Hydrochloric Acid; (*b*) with Sulphuric Acid.

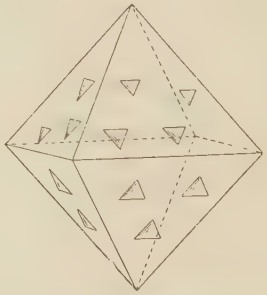


Fig. 287.—Diamond, Natural Etching.

depend upon the nature and concentration of the solvent. The rhombohedron-faces {100} of calcite, etched with hydrochloric acid, yield figures shown in Figs. 281 and 286 (*a*); treated with sulphuric acid they are etched as in Fig. 286 (*b*).

Experiments with hydrochloric acid on cylinders of calcite indicate that with a more concentrated solvent the etched faces are produced more readily and in greater perfection than with a dilute solvent.

Etched figures are not only produced by artificial means, they often occur in minerals as a result of the corrosion by the natural solvents (such as carbonic acid, or water acting under pressure at a high temperature), which play so important a part in the changes in the earth's crust.

The beautiful triangular figures which are often found upon the natural octahedron-faces of diamond are supposed to be of this nature (Fig. 287).

Precisely similar figures are produced on alum by merely passing a moist cloth rapidly over the surface of an octahedron of this substance. They are little pits whose sloping sides are facets belonging to a flat

three-faced octahedron like the vicinal faces mentioned on p. 110. Hence an octahedron of alum will always give a triangular light-figure (p. 110), whether it be the natural surface or an etched surface, since in either case facets of a flat three-faced octahedron are present.

7. **Pyro-electricity.** — A remarkable property of certain crystals is peculiarly characteristic of those which possess polar axes of symmetry, and it may most readily be observed in tourmaline.

If a crystal of tourmaline be heated, it is found that while the temperature is rising, one end (namely the upper end of Fig. 190) becomes negatively, and the other end positively electrified.

Tourmaline not being a conductor, these electrifications appear as statical charges upon the two ends. While the crystal is cooling their nature is reversed, the positive charge appearing at the upper end, and the negative at the lower end of Fig. 190. An ingenious method of observing these effects was devised by Kundt: a mixture of finely powdered red lead and sulphur is dusted or blown through a small sieve of fine muslin upon the crystal; during their passage through the sieve the particles become electrified by mutual friction, the sulphur negatively and the red lead positively; the former is then attracted towards those parts of the crystal which are charged with positive, and the latter to those which are charged with negative electricity. Thus in the tourmaline crystal of Fig. 190, while the temperature is falling the upper end becomes covered with the yellow sulphur, and the lower end with the red lead, so that the two regions are made clear to the eye.

Such a crystal is said to exhibit pyro-electricity. The two ends are distinguished as "analogous" and "antilogous"; the analogous end is that at which the nature of the charge is analogous to the change of temperature, addition of heat producing a positive, and withdrawal of heat a negative charge. Thus the lower end of Fig. 190 is that at which cooling produces a negative charge, and is therefore the analogous pole. It will generally be found that the more acute end of a tourmaline crystal is the antilogous, and the more obtuse end the analogous pole (*cf.* Fig. 682, p. 539).

The same property of pyro-electricity is possessed in a marked degree by the zinc silicate, hemimorphite, of Fig. 240, which used to be known by the name of "electric calamine." Here, also, the more acute end of the crystal is the antilogous pole.

Both these minerals are polar, that is to say, as explained above (p. 47), their principal axis of symmetry is geometrically dissimilar at its two ends—it has a certain polar character. In this direction they are also polar in a physical sense, as shown by their pyro-electric character. Now such crystals are only a particular example of the more general class comprising all crystals which are devoid of centro-symmetry; in any such crystal there are certain directions which are polar in character, although there may be other directions which are not polar. In the former the crystal will exhibit pyro-electricity if it be a non-conductor; in directions which are not polar it will not exhibit a pyro-electric character. In such crystals, therefore, if they be dusted with the mixed powders

during a rise or fall of temperature, certain parts will become covered with the red lead, and the opposite parts with sulphur; and Kundt's method enables us to explore the whole surface of the crystal at the same time.

A simple quartz crystal (Fig. 198 or 199) becomes positively electrified (yellow) on three alternate prism and pyramid edges (*viz.* those on which the small faces *s* and *x* do not occur, if the crystal be examined during cooling), and negatively (red) on the remaining edges. This indicates that the horizontal axes of symmetry in a quartz crystal are polar; on the other hand, the vertical axis of trigonal symmetry is not dissimilar at its two ends; the upper and lower vertices of the crystal are similar, and the crystal does not exhibit pyro-electricity in this direction. It will be evident, on consideration, that the existence of the horizontal symmetry axes is incompatible with any polarity in the vertical axis, since by rotation about them the two ends of the latter are interchangeable.

Again, a crystal of boracite (Fig. 84) becomes red on four of its corners, corresponding to one tetrahedron, and yellow on the remaining four corners, which correspond to the supplementary tetrahedron.

All the above observations lead to the same general result, that the physical properties of a crystal obey the laws of geometrical symmetry, in the sense that all the planes and directions in a crystal which are geometrically similar are also invested with the same physical characters as regards conductivity, elasticity, cohesion, solubility, or electrification. Hence it will be readily understood that it is always advisable, if not necessary, to confirm the results of goniometrical measurement by the application of one or more of the tests above described. Of these the etching and pyro-electric tests are extremely easy of application, and should never be neglected.

Certain of the physical properties, and notably that of pyro-electricity, are of special importance as enabling the absence of centro-symmetry to be detected.

Other properties, such as the rate of propagation of light, the elasticity and the conductivity for heat, though they vary in different directions, are apparently the same in opposite directions, even in crystals devoid of centro-symmetry. They may yet be of very great value in indicating the symmetry of a crystal, and may suffice to determine at least the *system* to which the crystal belongs, though they may not define its exact position among the 32 classes.

First and foremost of such must be ranked the optical properties, which we may now proceed to consider.

CHAPTER VI

THE OPTICAL PROPERTIES OF CRYSTALS

1. **Waves of Light.** — When light passes from one point A to another point B in a uniform medium, it may be regarded as a disturbance which travels along the straight line AB, like the wave-motion which may be sent along a rope hanging from the ceiling by shaking the loose end ; and the line AB along which the disturbance travels is called a ray of light.

Before a wave is started the particles of which the rope consists lie at rest on the straight line AB, but at any moment after the disturbance has spread along the line the same particles lie on a wave-line, as in Fig. 288 ; each particle has travelled to a certain distance right or left of its original position.

When, in the vibrating rope, the displacement attains its maximum at the point P, the particle which was originally at O has travelled to P with continually diminishing velocity, and has come to rest; being drawn back by its neighbours it then immediately begins to return with continually increasing velocity towards O. The velocity which it acquires carries it through O to an equally distant point R on the opposite side of the line AB. At this moment the particles originally on the line AB lie on the wave-line of Fig. 289. The particle then returns to P and the oscillation is repeated ; similar oscillations are made by every particle, and in this way is produced a series of waves which chase one another along the line AB, although each particle only vibrates backwards and forwards at right angles to AB. Whatever may be the change of state to which light is really due, the principles of wave-motion afford a very satisfactory geometrical description of most optical phenomena.

The intensity of any light may be supposed to depend upon the extent or " amplitude " of the vibrations, that is upon twice the displacement OP ; the intensity being proportional to the square of the amplitude. The colour of the light may be supposed to depend upon the distance between successive troughs or successive crests of the wave-line ; this distance is called the " wave-length," and is denoted by λ.

At any point along the line AB the " phase " of the wave at a given moment is defined by the displacement of the corresponding particle from its position of equilibrium, on AB, and the direction in which it is moving.

At any two points, such as A and S, which are separated by the interval λ, the phase is the same. The waves of Figs. 288 and 289 are said to differ in phase by half a wave-length or $\frac{\lambda}{2}$, because that of Fig. 289 is precisely what that of Fig. 288 would be if shifted along AB through a distance $= \frac{\lambda}{2}$, so that A would occupy the position A_1.

2. **Interference of Waves.**—When two waves of the same wave-length and in the same phase, but of different intensities, are caused to travel along the same line at the same time, a particle at O will be affected simultaneously by both wave-motions (Fig. 290); if then P be the point

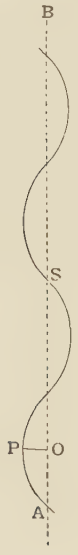


Fig. 288.

Fig. 289.

Difference of Phase, $\frac{\lambda}{2}$.

Fig. 290.—Resultant of Two Waves.

to which it would oscillate by virtue of one wave, and Q the point to which it would oscillate at the same moment by virtue of the other, it will actually move to R, where $OR = OP + OQ$. Hence the joint effect of the two wave-motions (I and II) will be to produce a resultant wave-motion (III) of the same phase and the same wave-length, but of greater intensity. The phase remains the same, for the troughs and crests of the constituent waves coincide, so that the troughs and crests of the resultant waves must also coincide with them.

Such combination of waves to form new waves is called "interference."

When the two waves which interfere differ also in phase, both the amplitude and the phase of the resulting wave will be altered.

Now when the two waves are equal in amplitude and wave-length,

but differ in phase by $\frac{\lambda}{2}$, as in Figs. 288 and 289, it follows that a particle such as O will be urged at the same moment to precisely the same extent in opposite directions, to P and to R, and must therefore remain at rest. This is true for every point on the line AB; the two waves will then destroy each other, and, if the analogy be complete, two waves of light related to each other in this manner will by their mutual action produce darkness. Hence if by any means two precisely similar trains of waves identical in wave-length, amplitude, and all other respects, can be made to differ in phase by half a wave-length, and to travel along the same line, they will completely destroy each other. The same will occur if the phase-difference is $\frac{3\lambda}{2}, \frac{5\lambda}{2}$; or any odd number of half wave-lengths.

Complete identity of the two trains of waves is secured by deriving them simultaneously from the same source of light.

To be of the same wave-length they must be of one and the same colour. Now ordinary white light is composed of lights of various wave-lengths; but a monochromatic light (or light of single wave-length) may be obtained by volatilising certain metallic compounds. A nearly uniform or monochromatic yellow light (a "sodium flame") is produced by heating any salt of sodium in the flame of a spirit lamp or Bunsen burner. Thallium salts may be used to produce a green, lithium salts to produce a red flame.

The corresponding wave-lengths are:

Lithium . .	$\lambda = 0{\cdot}000671$ mm.
Sodium . .	,, $0{\cdot}000589$ mm.
Thallium . .	,, $0{\cdot}000535$ mm.

Two trains of waves of the same wave-length and travelling along the same line, but differing in phase, may be obtained by causing one of two identical trains, derived from such a monochromatic source, either to traverse a longer path than the other or to travel for a time with less velocity, so that it lags behind.

We shall now consider a case of the production of interference depending on the first of these two methods, namely that of the colours shown by a thin plate or film, such as a soap-film, and by Newton's rings, and we shall return later to the second method when considering the action of crystals on light (p. 164).

3. **Colours of Thin Plates.**—Among the most familiar effects of interference are the colours shown by thin films, such as the iridescence of tempered steel, which is due to a thin layer of oxide, or the brilliant tints of a soap-bubble, or the coloured bands visible in glass or other transparent substances when they are traversed by fine cracks.

All such effects are known as the "colours of thin plates."

We shall consider first a thin film surrounded by air, such as that of a soap-bubble (Fig. 291).

Let AB, CD be the parallel surfaces of the film; consider a ray of

light OP incident at P; this is partly reflected at the surface, and partly refracted into the film; let NPN_1 be the normal to the surface at P. Then the reflected ray takes the course PQ, such that the angle of reflection QPN is equal to the angle of incidence $= OPN = i$; the refracted ray takes the course PR_1, where $N_1PR_1 = r$, the angle of refraction; let V be the velocity in air of the incident light and v its velocity within the film, then $\frac{\sin i}{\sin r} = \frac{V}{v} = \mu$, the index of refraction of the film. If the film consists of water surrounded by air, then μ is about 1·3.

The refracted ray on meeting the second surface of the film at R_1 is again partly reflected and partly refracted; the angle of incidence, and therefore also the angle of reflection of the reflected portion R_1S_1, is equal to r; consequently the latter meets the first surface again at S_1 with an

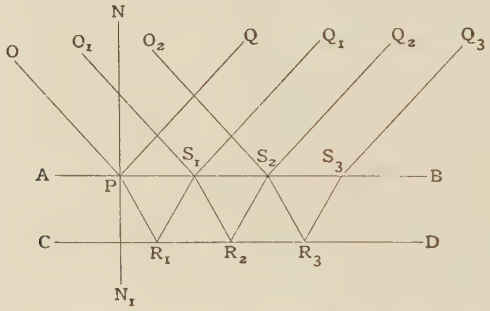


Fig. 291.—Reflection of Light by a Thin Plate.

angle of incidence r. Here again the ray is partly reflected and partly refracted.

The angle of emergence of the refracted ray S_1Q_1 is found as usual from the relation

$$\frac{\text{sine of incidence at } S_1}{\text{sine of refraction at } S_1} = \frac{\sin r}{\text{sine of refraction}} = \frac{v}{V} = \frac{\sin r}{\sin i}.$$

Hence i is the angle of emergence at S_1, and the ray S_1Q_1 is parallel to the original reflected ray PQ.

The ray reflected back into the film at S_1 behaves in all respects like the ray PR_1, to which it is parallel; it is reflected at R_2, meets the first surface again at S_2, and is there partly reflected along S_2R_3, and partly refracted out along S_2Q_2 parallel to S_1Q_1. Inside the film the course of the ray is always inclined at the angle r to the normal, and outside the film at the angle i.

Hence the incident ray OP gives rise to a series of rays which emerge in parallel directions at $S_1S_2S_3$, etc., after undergoing respectively 1, 3, 5, etc., internal reflections at the surfaces of the film.

Now the incident light being necessarily not a single ray, but a beam of parallel rays, any point such as S_2 is a point from which emerges not only a ray $O_1S_1R_2S_2Q_2$, which has suffered one reflection within the

film, but also a ray $O_2S_2Q_2$, which has been directly reflected at S_2. Of these two rays the first has travelled a certain distance from the source to S_1 in air, and twice the distance S_1R_2 in water, while the second has travelled from the source to S_2 in air before they meet at S_2. When the former ray rejoins the latter at S_2 they unite as coincident rays of light, resembling each other in all respects save that they have traversed different distances, in air and water, and that the former ray has experienced one *internal* reflection while the latter has experienced one *external* reflection, and they will consequently differ in phase.

Let the light employed be monochromatic light of wave-length λ; the difference of path depends only upon the angle of incidence of the light, upon the thickness of the film, and upon its refractive index. If then films of different thickness be successively employed without changing the angle of incidence, it will be possible to find one thickness for which the difference of phase between the two rays on emergence is exactly equal to $\frac{\lambda}{2}$. In this case the rays will so interfere as to produce complete darkness. For a greater thickness the difference of phase may be $\frac{3\lambda}{2}$, and there will again be complete interference. This will also be the case for successive thicknesses, which correspond to a difference of phase $\frac{5\lambda}{2}$, $\frac{7\lambda}{2}$, etc. With films of intermediate thickness the interference will be only partial, and will not cause extinction of the light. If the thickness corresponds to a phase-difference of λ, 2λ, or any whole number of wave-lengths ($n\lambda$), the effects of the two rays will be added, and an increased brightness will result.

These changes can be observed, occurring in the reverse order, in a soap-film which is gradually becoming thinner just before it breaks. A more convenient method is to use a permanent film of gradually varying thickness, *i.e.* one which is slightly wedge-shaped. The experiment can be made by pressing a glass plate (microscope slide) upon a nearly flat glass lens or watch-glass (Fig. 292), illuminating it by the monochromatic yellow light of a sodium flame (S), and viewing it by the obliquely reflected light; the film of air between the plate and the watch-glass varies in thickness regularly and equally in all directions from the point of contact, and has a constant thickness on any circle of which this point is the centre.

A series of black and yellow circular rings will now be observed (Fig. 293), whose centre is occupied by a black spot corresponding to a film of almost no thickness. This spot is due to the interference of light internally reflected from the lower surface of the glass plate with that reflected from the watch-glass immediately beneath it. The difference of path is here practically zero; but the central spot is black and not bright owing to the fact that an internal reflection produces a difference of phase $\frac{\lambda}{2}$ as compared with an external reflection, and this

is to be added to the difference of phase due to the difference of path. The first black ring is due to the extinction of the light which has traversed a thickness of film just sufficient to produce the difference of phase λ, which, together with that due to one internal reflection, amounts to $\frac{3\lambda}{2}$; the second is due to a total difference of phase $\frac{5\lambda}{2}$; the third to one of $\frac{7\lambda}{2}$, and so on; for each of which differences the light is extinguished.

Next suppose ordinary white light and not monochromatic light to be used; again a series of circular rings surrounding the point of contact will be seen, but the rings are now brilliantly coloured, like the bands of colour seen by daylight in the soap-bubble film first considered. The rings produced in this experiment are known as Newton's rings; the

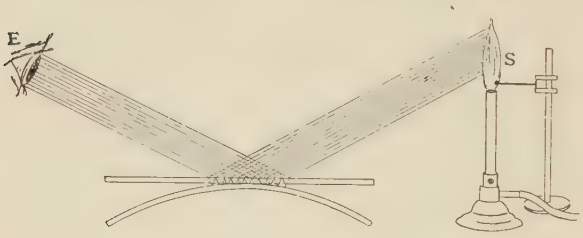


Fig. 292.—Formation of Newton's Rings.

Fig. 293.—Newton's Rings.

succession of colour, which was first studied by Newton, must receive our closer consideration.

4. **Newton's Scale of Colours.**—White light is a mixture of lights of various colours or wave-lengths. These travel with different velocities and are differently refracted; so that white light may be separated by refraction through a prism into the various colours of the spectrum, ranging from the violet, of smallest wave-length and greatest refrangibility, through blue, green, yellow, and orange to the red, of greatest wave-length and least refrangibility. When the interference-rings are observed with monochromatic blue light of small wave-length, the successive thicknesses of film, which correspond to differences of phase of $\frac{\lambda}{2}, \frac{3\lambda}{2}$, etc., are smaller than those for yellow light, and these again are smaller than those for red light; hence the rings seen with blue light will be smaller in diameter than those seen with yellow light, and the latter smaller than those seen with red light.

Newton's rings, as seen by ordinary daylight, are simply the result of the superposition of all the effects due to light of different colours, the closely packed rings of blue light upon the wider rings of yellow and still wider rings of red light, and the resultant effect is a series of coloured rings which succeed each other in a definite order.

At a point where the first dark ring appears in blue light, light of this

colour is destroyed by interference owing to a total phase-difference of $\frac{3\lambda}{2}$, and in white light the colour seen will be a residual colour, consisting of white *minus* blue. This colour, called the " complementary " to blue, is a brownish yellow. Slightly further from the centre, green will be cut out, and the colour seen will be its complementary—violet. Further still, red will be wanting and the colour will be blue. If the spectrum of one of these residual colours were examined, it would be found to be crossed by a dark band, resembling an absorption-band, in the position corresponding to the colour destroyed.

At a point still further from the centre, the thickness of the film may be such that the total phase-difference is $\frac{5\lambda}{2}$ for violet light, and $\frac{3\lambda}{2}$ for red light, so that here both violet and red will be cut out and the spectrum of the residual colour will show two dark bands. Thus, as the thickness of the film increases the number of colours destroyed by interference will increase. The residual colours become paler and eventually are indistinguishable from white, since part of each constituent colour of white light is removed (as shown by the spectrum being crossed by numerous bands), while the proportions of the different colours are much the same as in the original white light.

The following succession of colours may be distinguished :

Black.	1st order.	Greenish blue.	3rd order.
Grey.		Bright green.	
White.		Yellowish green.	
Brownish yellow.		Pink.	4th order.
Purplish red.		Pale leek-green.	
Violet.	2nd order.	Salmon pink.	5th order.
Blue.		Pale greenish blue.	
Light greenish yellow.		Flesh-colour.	6th order.
Yellow.		Pale greyish green.	
Magenta.		Pale pink.	7th order
Violet.		Very pale greenish grey.	
		Pinkish white.	
		White of higher orders.	

The colours near the centre, as far out as the first violet ring, are called colours of the 1st order, those as far as the next violet ring are colours of the 2nd order and so on—the transition from each order to the next higher coinciding with the passage from a reddish to a bluish or greenish tint.

The colours of the first order are somewhat dull, those of the second and third orders are the most vivid ; the succeeding colours become paler, until after the sixth or seventh order they merge into the so-called " white of higher orders." An experienced eye can easily recognise the various colours of the first three orders.

In the white of the 1st order, between the central black spot and the

first colour visible (yellow), all colours are present, as the phase-difference due to the difference of path is less than λ for all colours, and with the $\frac{\lambda}{2}$ due to the internal reflection gives a total phase-difference of about a whole wave-length for all colours.

These coloured rings are to be compared with the very similar rings which are produced by a uniaxial crystal in a polarising microscope, as described on p. 169 (*cf.* Fig. 376).

If a simple wedge-shaped film be used, *e.g.* the film of air between two glass plates AB, CD (Fig. 294), which have been cemented together, and have become slightly separated at the end BD, the colours no longer form circles but straight bands, as in Fig. 295, the colours and the sequence of the various orders being, however, precisely the same as before. This series of bands is to be compared with those given by a quartz wedge in the polarising microscope as described on p. 166.

A series of colours resembling those of Newton's rings will result from any contrivance which causes the interference of white light by continually increasing differences of phase; for this leads to the successive extinction of light of all different wave-lengths in the same sequence.

Fig. 294.—Wedge-shaped Air-film.

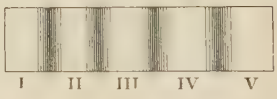


Fig. 295.—Interference-bands produced by a Thin Wedge.

A very important case will be considered later in the interference-phenomena of crystals produced through the agency of "polarised light" (see p. 164).

5. **Plane-polarised Light.**—A rope suspended by one end may have a wave-tremor sent along it in various ways; the free end may be shaken with a simple backward and forward movement along one line, waves will then be produced in which all the oscillations take place in one plane; or the free end may be shaken with a circular or irregular movement, waves which may possess the same wave-length and amplitude as before will then travel along the rope, only with this difference that each particle no longer oscillates along one line, but describes a circle, ellipse, or other curve about its original position.

Ordinary light may be regarded as consisting of sets of waves of the latter sort, whose movement is irregular or in constantly varying directions, but by appropriate means it is easy to obtain a particular sort of light, which may be regarded as due to oscillations in one plane. This is known as "plane-polarised light," and is distinguished from ordinary light by the following among other properties.

Let a slice of tourmaline, cut parallel to the principal axis of the crystal of Fig. 190, be placed in its path, so that the light is incident upon it perpendicularly; then if the slice of crystal is rotated in its own plane it will be found that the light is only completely transmitted when the axis

lies in one particular direction ; and that when the plate is turned through 90° from this position the light is completely absorbed by the crystal. Ordinary light, on the contrary, is transmitted equally whatever position the axis of the tourmaline may occupy as the plate is rotated in its own plane.

Plane-polarised light may be produced in various ways. When light

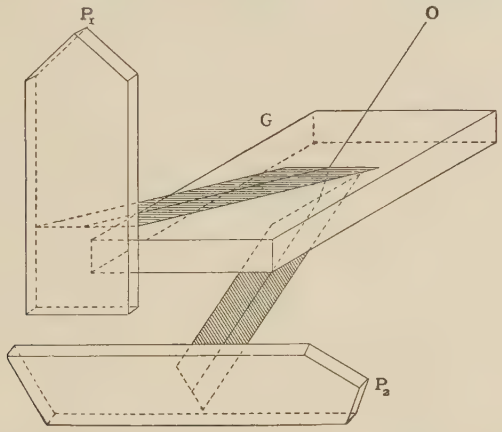


Fig. 296.—Examination of Polarised Light by a Tourmaline Analyser.

from the direction of O is incident on a surface, G, of ordinary glass at an angle of about 56° (Fig. 296), the reflected beam is plane-polarised ; if examined by means of the plate of tourmaline it is found to be completely absorbed when the axis of the tourmaline lies in the plane of incidence, as at P_1 of Fig. 296, and to be transmitted when the axis of the crystal is perpendicular thereto.

The light transmitted through the glass is also plane-polarised, but its properties are different from those of the reflected ray ; for it is absorbed by the tourmaline when the axis of the crystal is *perpendicular* to the plane of incidence, as at P_2 of Fig. 296.

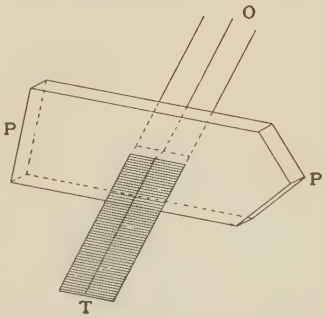


Fig. 297. –Polarisation by Tourmaline.

The reflected light is said to be "polarised in the plane of incidence," and the refracted light is therefore said to be polarised in a plane perpendicular to that of incidence.

Another way of obtaining plane-polarised light is to transmit ordinary light O through a plate of tourmaline cut, as above, parallel to the axis of the crystal (Fig. 297). The transmitted light T is found to possess the properties of light reflected from glass so placed that the plane of incidence is perpendicular to the axis of the tourmaline. It is therefore said to be polarised in this plane.

If the properties of light be compared with those of a vibrating medium, the vibrations of plane-polarised light may be regarded as probably taking place at right angles to the plane of polarisation.

In light reflected from glass they are therefore perpendicular to the plane of incidence ; in the refracted light they are in the plane of incidence ; in light which has been transmitted through a plate of tourmaline they are parallel to the principal axis. These directions are indicated by the shading in Figs. 296, 297.

Bearing in mind that the conception of light as due to the vibrations of particles at right angles to the path of the light may be no more than a geometrical representation of some recurrent change of state which is not really a vibration, we may continue to speak of a ray of light as due to such vibrations, and of a plane-polarised beam as due to vibrations perpendicular to the plane of polarisation ; and of a tourmaline plate as only transmitting vibrations which take place parallel to its axis (as in Fig. 297).

6. **Resolution and Analysis of Polarised Light.** — When light is transmitted through a crystal of tourmaline PP (Fig. 297) it emerges

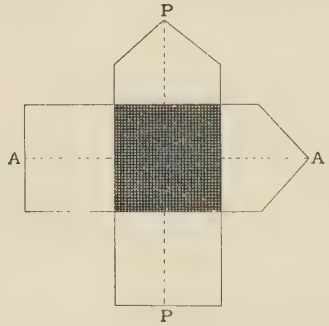


Fig. 298.—Polariser and Analyser crossed.

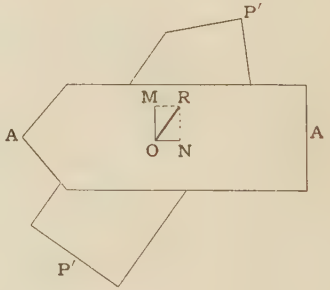


Fig. 299.—Polariser and Analyser inclined.

plane-polarised, the vibrations taking place parallel to PP. If another tourmaline crystal be placed upon this, with its axis AA perpendicular to the axis PP of the first tourmaline (Fig. 298), no light emerging from the first crystal can penetrate the second, since the latter can only transmit light vibrating parallel to AA, and where the two crystals overlap there will be darkness. If, however, the lower crystal be turned round until it is parallel to the upper one, then the polarised light which emerges from the former will pass unchanged in character through the latter. Let the lower crystal be now placed in some intermediate position as P′P′ (Fig. 299). A vibration which would transfer a particle of a vibrating medium from O to R may be supposed due to the simultaneous action of two vibrations, one of which would transfer the particle to M, and the other to N. In other words, the vibration OR may be *resolved* into two component vibrations along the directions OM and ON of Fig. 299 respectively, just as a force may be resolved into component forces along

two directions at right angles to each other, and its effect studied by observing the separate effects of these two components. The amplitudes of the component vibrations are given by the lengths of the sides of the parallelogram MONR.

Now of the two vibrations into which OR is supposed to be resolved, the component along ON is transmitted by the second tourmaline, while the component along OM is absorbed. The result is that if a plane-polarised ray, vibrating along P′P′ with semi-amplitude OR, passes into AA, part of it is transmitted as a plane-polarised ray with semi-amplitude ON. As the lower crystal is rotated from the position P′P′ to the position PP, more and more of the light is cut off by the upper crystal, until in the latter position it is completely absorbed.

A tourmaline crystal or other contrivance used, like PP, to produce a beam of plane-polarised light is called a "polariser"; that used like AA to examine the same is called an "analyser."

When their planes of polarisation (and therefore also their axes AA, PP) are at right angles, darkness is produced, and the polariser and analyser are said to be "crossed" (Fig. 298).

7. **Action of Crystals on Light.**—When light enters a crystal it experiences certain peculiar modifications which are very remarkable and give rise to the most beautiful effects; these have been minutely studied; they have constituted the basis of the wave theory of light, and they have subsequently proved to afford one of the most subtle means of studying the crystalline structure of transparent crystals, and hence also of identifying mineral species.

When a ray of light enters a crystal belonging to the cubic system it is refracted just as it would be on entering a piece of glass or other amorphous substance, and the refracted ray obeys the ordinary laws of refraction; it therefore lies in the plane of incidence, and, if i be the angle of incidence, and r the angle of refraction, then $\frac{\sin i}{\sin r}$ is the index of refraction of the crystal for the particular light employed, and the refractive power is measured by this index. The index of refraction is the same whatever be the direction of the ray in the crystal. A cubic crystal is therefore said to be "singly refracting" or "optically isotropic."

But when a ray of light enters a crystal belonging to any other system it is in general divided into two refracted rays, one at least of which does not necessarily lie in the plane of incidence. Such crystals are said to be "doubly refracting," or "optically anisotropic," and the angular divergence between the two rays produced is different for different substances and also for different directions in the same crystal.

A crystal whose double refraction is strong may produce so large an angular divergence of the two rays that an object viewed through it will appear double, one image being produced by rays travelling in the one direction and a second by rays travelling in the other. This phenomenon was first observed and studied in the clear transparent variety of calcite known as "doubly refracting spar" or "Iceland spar," which was found in large masses at Eskifjördhr in Iceland.

8. **Double Refraction in Iceland Spar.**—If a cleavage-rhombohedron of Iceland spar (Fig. 300) be placed over a black spot on a sheet of white paper the spot will appear double (Fig. 301, where the crystal is lying on a face parallel to ZMEN). Of the two images one (*o*) appears to occupy the position in which it would be seen through a plate of glass or other isotropic substance of the same refractive power; the corresponding ray

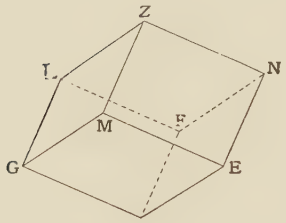


Fig. 300.—Iceland Spar.

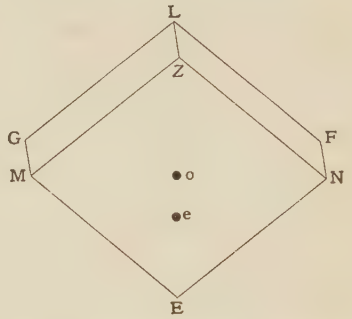


Fig. 301.—Double Refraction by Iceland Spar.

is therefore refracted according to the ordinary laws of refraction and is called the "ordinary" ray; the other image (*e*) appears shifted away from the summit Z of the rhombohedron, in one of the planes of symmetry of the crystal, *i.e.* along the shorter diagonal ZE of the rhombohedron-face. Even when the crystal is viewed perpendicularly to the rhombohedron-face

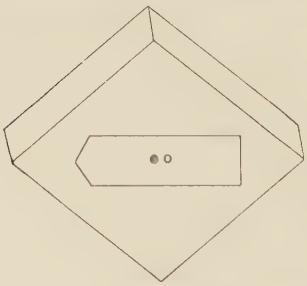


Fig. 302.

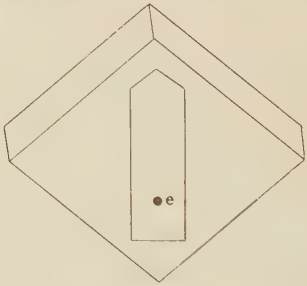


Fig. 303.

Analysis of Light transmitted through Iceland Spar.

the two images are still visible; the ordinary image is seen vertically through the face without any displacement, but the other image is still shifted away from the summit; the latter therefore corresponds to a ray which obeys some totally distinct or extraordinary law of refraction, and this is called the "extraordinary" ray. The course of the rays through the crystal is shown in Fig. 304.

If now these images be examined through the tourmaline analyser, it will be found that as the tourmaline is turned round the ordinary image disappears when the principal axis of the tourmaline is parallel to

the shorter diagonal of the rhombohedron-face (Fig. 303), and the extraordinary image disappears when the axis is parallel to the longer diagonal (Fig. 302).

This proves that these images are due to two plane-polarised rays, the ordinary ray polarised in the plane of symmetry, the extraordinary polarised perpendicular thereto.

Hence a ray of light entering a rhombohedron of calcite is separated into two polarised rays—an ordinary ray whose vibrations may be regarded as parallel to the longer diagonal of the rhombohedron-face, and an extraordinary ray due to vibrations along the shorter diagonal of the face.

A more satisfactory way of examining a crystal such as calcite would be to permit the incident light to pass through it *in one direction only* by means of two screens, one having a hole at P and the other a hole at Q (Fig. 305); one screen being placed on one face of the crystal and the

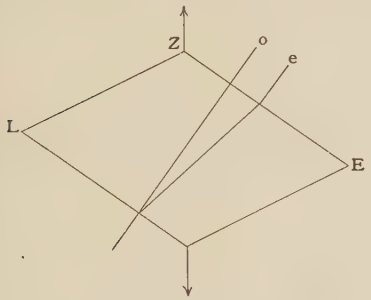


Fig. 304.—Double Refraction in Iceland Spar.

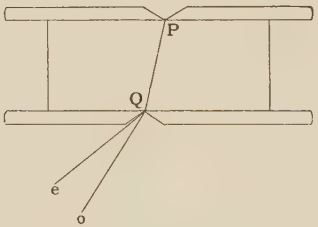


Fig. 305.—Double Refraction.

other on the parallel face, so that the light can only traverse the crystal in the direction PQ. By moving the screens the line PQ might be given any required direction. It would then be found, in general, that light traversing the crystal in the direction PQ would emerge as two refracted beams, *e* and *o*, polarised at right angles to each other and travelling in different directions, so that PQ is a direction along which two rays are transmitted in the crystal—a direction of so-called double refraction.

When crystals of calcite are examined in all possible directions, it is found they are always doubly refracting except when the light travels along the principal axis. In this one direction, perpendicular to the basal plane, there is no division of the transmitted light into two plane-polarised rays—no double refraction—but in all other directions the transmitted light consists of two polarised rays whose planes of polarisation are at right angles to each other.

9. **Double Refraction in Crystals in General.**—What has been stated above of calcite is equally true of all crystals belonging to the hexagonal system, or to the tetragonal system. Although their double refraction may not be so marked as that of calcite, they will in general transmit light as two plane-polarised rays travelling in a given direction within the crystal, an ordinary and an extraordinary ray; further, they

all have one direction along which there is no double refraction, namely, the principal axis. A direction along which there is no double refraction is here called an "optic axis"; and minerals belonging to these systems, since they possess only one optic axis, are said to be "uniaxial."

Crystals belonging to the orthorhombic, monoclinic, or anorthic system are also doubly refracting, but light traversing one of these crystals in any direction is in general transmitted as two extraordinary plane-polarised rays, neither of which obeys the ordinary laws of refraction. Crystals belonging to these systems differ from uniaxial crystals in that they possess *two* directions which exhibit most of the features of the optic axis of a uniaxial crystal; they are consequently called "biaxial."

Crystals may then, in the first place, be divided into the following three important groups:

Cubic crystals	. . . . .	optically isotropic
Hexagonal and tetragonal crystals	. . .	,, uniaxial.
Orthorhombic, monoclinic, and anorthic crystals		,, biaxial.

The property possessed by tourmaline of transmitting at right angles to its axis plane-polarised light results simply from the fact that of the two rays produced in the crystal, one (the ordinary) is completely absorbed, and only the extraordinary ray is transmitted, the vibrations of which may be supposed to take place along the principal axis of the crystal.

10. **Examination of Minerals in Polarised Light.**—The optical characters of minerals are best examined by observing either thin sections cut out of their crystals in known directions, or natural sections obtained by cleavage, or natural plates bounded by a pair of parallel crystal faces For this purpose it is necessary to use a microscope fitted with a polariser and an analyser.

The following are the special requirements of a microscope for mineralogical use: a rotating stage on which the crystal section is placed, a polariser below the stage, and an analyser above the stage, the latter being either in the tube or above the eyepiece. Both polariser and analyser should be movable, so that they can be inserted or withdrawn at will. The microscope should also be supplied with a lens, or system of lenses, which can be inserted immediately below the section so as to concentrate the light after it has passed through the polariser and form a convergent beam within the crystal if desired.

Since good plates of tourmaline are difficult to procure, and have the disadvantage of being coloured, the contrivance known (from the name of its inventor) as a "nicol prism" is generally used for both polarising and analysing the light.

A nicol prism is made from a cleavage-rhombohedron of calcite about three times as long as it is broad (Fig. 306; compare Fig. 300): this is cut in half along a plane ZZ′ joining two opposite corners (actually inclined at 22° to the longer edge ZL of the prism); the two halves are then cemented together with Canada balsam. The ends of the prism

are not exactly parallel to the natural cleavage-faces, but are ground at an angle of 2° 52′ to these, and are perpendicular to the plane of section ZZ′. The effect of this construction is that when the two rays, *o* and *e* (Fig. 307), which result from a ray of light entering the prism at its lower end, reach the film of Canada balsam, one, namely the extraordinary ray, for which the refractive index of the crystal is in this case slightly less than that of the balsam, is refracted through it and emerges as a plane-polarised ray vibrating parallel to the shorter diagonal of the prism ; but the ordinary ray, for which the refractive index ($\omega = 1{\cdot}658$) is above that of the balsam, meets the film at a larger angle of incidence, and one which exceeds 69° 4′, the angle of total reflection for that ray incident on balsam from calcite ; this ray is therefore reflected to the side of the prism and is there absorbed, the surface being blackened for the purpose. The prism

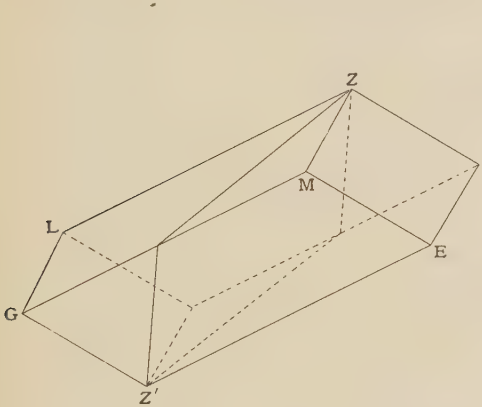


Fig. 306.—Nicol Prism.

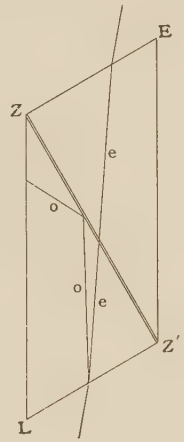


Fig. 307.—Section of Nicol Prism.

consequently (like the tourmaline plate) transmits only a single beam of plane-polarised light, the vibrations taking place along its shorter diagonal.

In the ordinary mineralogical microscope a nicol prism is mounted below the stage on an arm by which it can, if necessary, be swung out of the way ; and another nicol is mounted on a sliding piece in the tube. One or each of these is mounted in a ring so that it can be rotated and set with its plane of polarisation at any desired angle to that of the other ; but as a rule the two nicols are kept " crossed," *i.e.* with their planes of vibration at 90° to one another.

When a low-power objective is used and the converging system of lenses or " condenser " is not employed below the stage, all the light which enters the eyepiece has traversed the crystal in one direction, since all the rays have travelled from the mirror to the objective approximately parallel to the axis of the microscope ; a crystal observed in this way is said to be examined in " parallel light." When, however, the condenser is inserted below the stage, the light from the mirror is made to converge

and traverses the crystal in different directions. A high-power objective (a quarter-inch or higher) must then be used, by which the rays are brought to a focus and transmitted, through another lens, to the eyepiece. The crystal is then said to be examined in "convergent light."

The following remarkable phenomena are to be observed.

11. **Examination in Parallel Light.** — The nicols being crossed, no light is transmitted through the microscope. When any isotropic substance, such as a plate of glass, is placed on the stage the field remains dark. Any crystal which behaves in this way, or is "inert," in whatever direction it is viewed, is at once known to belong to the cubic system. When, however, a crystal belonging to any other system is placed upon the stage the field in general becomes bright, showing that, on account of the double refraction of the crystal, the plane-polarised light issuing from the polarising nicol becomes partially transmissible through the analyser.

Suppose the crystal to be a very thin section of colourless calcite cut parallel to its principal axis; viewed by a low power between crossed nicols the section will in general appear coloured; if it were ground thinner and viewed again in the same way the tint would be found to have changed, and would be probably more vivid. Hence the colour depends upon the thickness of the section.

If a number of sections, each thinner than the preceding, were examined in succession the tints would be found to vary through all the successive colours of Newton's scale from the higher to the lower orders; in other words, as the crystal section becomes thinner the tints follow the order of those resulting from interference in a thin film as it decreases in thickness.

If now the stage be rotated it will be found that the light transmitted retains the same tint but varies in intensity, and four times during a complete rotation it is completely extinguished. The four positions in which this occurs are called the "positions of extinction," and are at right angles to each other; in two of them the axis of the crystal is parallel to the shorter diagonal of the polariser; in the other two it is at right angles to this direction.

Almost all sections of calcite examined in this way exhibit the same characters: the crystal appears bright between crossed nicols, and is extinguished in four positions, perpendicular to each other, as it is rotated in its own plane. The colour depends upon the thickness of the section, which appears quite colourless when sufficiently thick; it depends also upon the direction in which the section is cut from the crystal.

Only when the section is cut perpendicular to the axis are the appearances different; the crystal then remains dark during the complete rotation of the stage. Remembering that calcite is a uniaxial mineral and that this section is perpendicular to the optic axis, so that the light which traverses it in that direction does not experience double refraction, we conclude that in this direction there is no transmission of light through the crossed nicols, because there is no double refraction in the crystal, and that the crystal is dark for the same reason as a cubic crystal.

Passing to biaxial minerals we find precisely similar phenomena, only with the difference that there are now *two* sections which remain nearly dark, like isotropic substances ; these are the sections cut perpendicular to each of two optic axes.

In general, therefore, a section of any crystal which does not belong to the cubic system, when examined in parallel light between crossed nicols, transmits light of a certain tint depending (1) upon its thickness, and (2) upon the direction in which it is cut out of the crystal ; but as the section is rotated in its own plane there are four positions of extinction, which are perpendicular to each other. A section cut perpendicular to an optic axis remains nearly dark, or is inert, when rotated between crossed nicols.

12. **Examination in "Convergent Light."**—In the examination by parallel light the objective is so placed that the crystal is in focus, and the effects produced by the passage of light through the crystal, namely the tint and the extinction, are observed at the same time with the crystal itself.

In the examination with so-called " convergent light " it is desired to observe the effects produced upon rays which have travelled in different directions through the crystal, and it is no longer necessary to view the crystal itself at the same time.

The effect to be observed at any point in the field is due to the interference of rays which have traversed the crystal in a certain direction, which is different for different points of the field. The effect is produced in a plane above the objective where parallel rays are brought to a focus, as described below on p. 169.

The different points in the field correspond to rays which have followed different directions in the crystal, and all these points taken together constitute a coloured figure. It will be found, however, that this figure, being in the principal focal plane of the objective, is formed too low in the tube to be viewed by the eyepiece ; the effects produced by convergent light are to be observed by removing the eyepiece, when the coloured figure is seen near the bottom of the tube, just above the objective ; or, more conveniently, by inserting a supplementary lens of appropriate focal length (known as a " Bertrand lens ") at some point between the objective and the eyepiece. Another way of seeing the effects produced in convergent light without removing the eyepiece, in a microscope which is not provided with the necessary lens in the tube, is to hold an ordinary hand-lens above the eyepiece ; the coloured image will then be seen conveniently magnified when the lens is held at the right height above the microscope.

Many sections will now be found to produce systems of the most beautifully coloured and regular rings, known as " interference-figures."

A section perpendicular to the optic axis of a uniaxial crystal gives rise to a black cross intersecting a series of circular coloured rings (Fig. 376) resembling the series of Newton's rings ; a section perpendicular to an optic axis of a biaxial crystal presents a black bar intersecting a series of slightly oval rings ; a section equally inclined to the two optic axes of a

biaxial crystal shows two dark bars or " brushes " surrounded by a series of oval or lemniscate rings (Figs. 344-348).

We have now to consider how these interference-figures are produced. For this purpose it will be necessary to consider the velocity and condition of the light traversing the crystal.

13. **Propagation of Light in Different Directions: The Wave-surface.**— The study of refraction has led to the conclusion that within a non-crystalline medium, such as glass, or a cubic crystal, a luminiferous wave-motion starting from a centre of disturbance O would spread with equal velocity in all directions. After a certain interval from the moment of its leaving O the disturbance will have reached the surface of a sphere whose centre is at O, and at all points lying on the surface of this, or any sphere described round O as centre, the phase will be the same. Such a surface is called a " wave-surface." At any point on the wave-surface the ray, *i.e.* the line along which the light has travelled thither from O, is the radius of the sphere, and is therefore perpendicular to the wave-surface.

Since it is impossible to isolate a single ray, we have to deal in optical experiments with a beam or pencil of rays. When the light starts from a point, as above, the beam is divergent or conical, and the " wave-front " or portion of the wave-surface enclosed by the beam is convex. The rays may be rendered parallel (as by passing through a convex lens), and the beam then becomes cylindrical and the wave-front plane. Consider then a small cylindrical beam travelling in a non-crystalline medium; the points which are in the same phase, *i.e.* the points which in the language of the wave theory at a given moment are all swinging together in the same direction, lie in the plane of the circle AB which is perpendicular to the beam (Fig. 309). This plane may be called the " front of the beam."

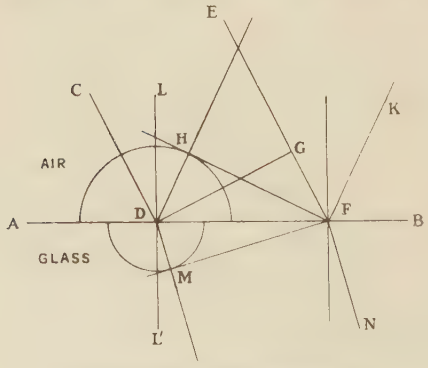


Fig. 308. Huygens' Construction for Reflection and Refraction.

The behaviour of a beam of light in respect of reflection or refraction may be ascertained by the help of the following construction, which was given by Chr. Huygens in his *Treatise on Light* (1690). Let AB (Fig. 308) be the surface between two isotropic media, *e.g.* air and glass, its plane being perpendicular to the paper; and let CD, EF be a parallel beam of light, incident obliquely on the surface. The successive wave-fronts of this beam will be planes perpendicular to CD and EF, *e.g.* DG, and all points on any such plane will be in the same phase. The ray CD will meet the surface sooner than the ray EF, by the time taken by the light to traverse the distance GF, and in the interval a wave-motion will spread

outwards from D both in the air and in the glass. By the time the ray EG has reached F this wave-motion will have travelled a distance equal to GF in the air, and a distance equal to $GF \times \frac{v}{V}$ in the glass, where V is the velocity of light in air and v its velocity in the glass. If a hemisphere be described round D with radius DH, equal to GF, the tangent plane to this through F, *viz.* FH, will be the direction of the new wave-front in the air; and the radius DH, through the point of tangency, will be the direction of the corresponding reflected beam DH, FK. The triangles DHF, FGD are similar, so that the angles DFG, FDH are equal, and the complementary angles LDC, LDH are also equal; whence follows the ordinary law of reflection, that the angles of incidence and reflection are equal.

Similarly, if a hemisphere of radius DM, equal to $GF \times \frac{v}{V}$, be described round D, the tangent plane FM will be the direction of the new wave-front in the glass, and the radius DM will be the direction of the refracted beam, DM, FN. From the triangles MDF, GFD it will be seen that $\frac{\sin LDC}{\sin L'DM} = \frac{\sin FDG}{\sin DFM} = \frac{GF}{DM} = \frac{V}{v}$, *i.e.* that the ratio of the sines of the angles of incidence and refraction are constant, and equal to the ratio of the velocities of light in air and glass. Thus the construction leads also to the ordinary law of refraction.

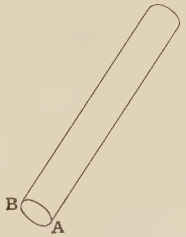


Fig. 309.—Beam and Wave-front in Air.

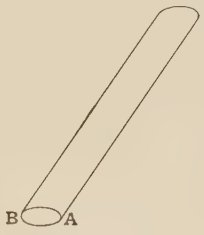


Fig. 310.—Beam and Wave-front in Crystal.

In a doubly refracting crystal, on the other hand, light, starting from a point, travels in general with different velocities in different directions, and points at which the phase is the same lie, not upon a sphere, but upon some other closed surface, whose tangent planes are not in general perpendicular to the corresponding radii. The wave-front is therefore inclined to the direction of the ray; and, in a cylindrical beam, points which, at a given moment, are in the same phase, lie in an oblique plane such as that of the ellipse AB (Fig. 310). The line perpendicular to the wave-front may be called the *direction of the wave*, or the *wave-normal*, as contrasted with the *direction of the ray*. Moreover, in a given direction there can usually travel two rays, having different velocities. Both rays are plane-polarised and their vibrations take place in planes perpendicular to one another. Thus the wave-surface is double, and consists of two "sheets" having a common centre but differing in form. In uniaxial crystals the wave-surface of the ordinary rays is spherical, while that of the extraordinary rays has the form of a spheroid, which is formed by rotating an ellipse about its major or minor axis, and which touches the sphere at the ends

of this axis. The axis of rotation is always parallel to the principal axis of the crystal. A section of such a wave-surface by a plane through the principal axis will have one of the outlines shown in Figs. 311, 312.

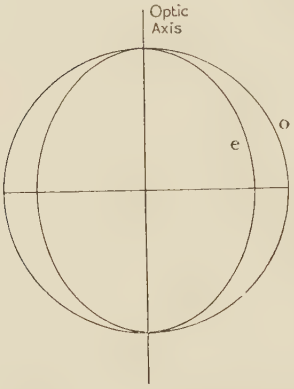


Fig. 311.—The Wave-surface of a (positive [1]) Uniaxial Crystal.

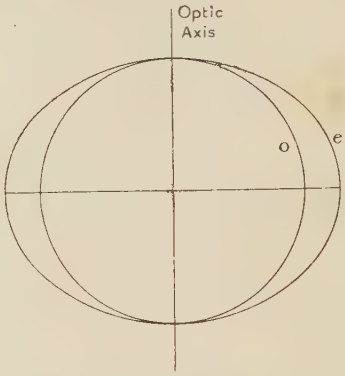


Fig. 312.—The Wave-surface of a (negative [1]) Uniaxial Crystal.

In order to trace the path of the rays in a uniaxial crystal, this double wave-surface must be used in place of the sphere in the Huygens construction. The spherical sheet gives the path of the ordinary ray, the spheroid gives that of the extraordinary ray. Fig. 313 shows the case

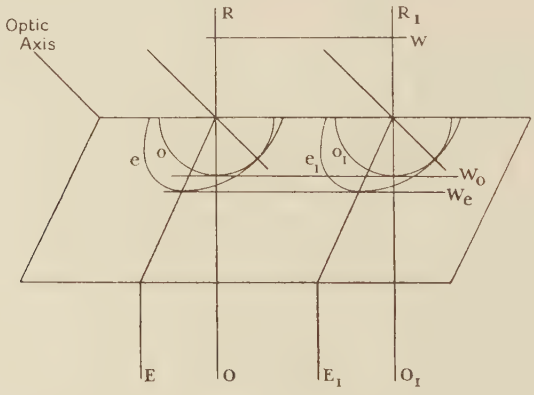


Fig. 313.—Double Refraction by a Cleavage-plate of Calcite.

of a plate of calcite bounded by the cleavage-faces (*cf.* Fig. 304), where the light is incident perpendicularly on the surface.

The incident wave-front W is here parallel to the surface of the plate, and all the rays composing the beam, such as R, R_1, enter the crystal simultaneously in the same phase and give rise to the simultaneously

[1] The explanation of the terms positive and negative will be found on p. 176.

expanding wave-surfaces o, e, o_1, e_1. The ordinary and extraordinary wave-fronts W_o, W_e in the crystal are the tangent planes to these, and are parallel to the surface of the plate, while the rays are represented by the radii drawn to the points at which these planes touch the respective wave-surfaces. The ordinary rays O, O_1 traverse the plate without deviation, but the extraordinary rays E, E_1 are refracted as shown. On emerging the latter resume their original direction, becoming again perpendicular to their wave-front.

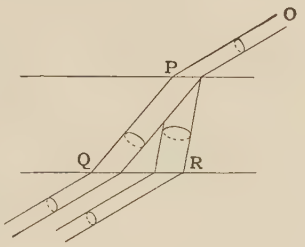


Fig. 314.—Double Refraction.

In biaxial crystals the wave-surface has a more complex form, which will be discussed later (p. 159).

The Huygens construction shows that when the wave-front of the incident beam is parallel to the refracting surface it undergoes no change of direction on entering the new medium (though the *beam* may be refracted, as in Fig. 313); but if it is not parallel to the surface the change in the velocity of propagation causes it to swing round and take up a new direction, which is more nearly parallel to the surface if the velocity is reduced (Fig. 308), and *vice versa*.

Refraction of an oblique beam OP by a plate of crystal is represented by Fig. 314. During the passage of the two refracted beams PQ, PR through the crystal their fronts are, in general, inclined, and unequally inclined, to the rays of which they consist. After emergence from the crystal the fronts are again perpendicular to the two beams, one of which has lagged behind the other, so that they would be in a condition to interfere, were it not that the vibrations of the one are at right angles to those of the other, instead of being parallel with them.

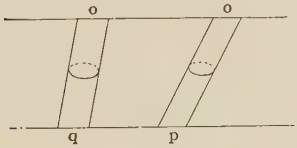


Fig. 315.—Beams in Crystal inclined: Wave-fronts parallel.

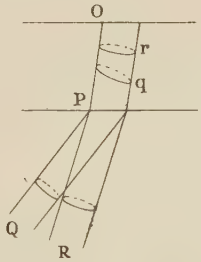


Fig. 316.—Beams in Crystal parallel: Wave-fronts inclined.

It must be observed that two beams which are inclined to one another within the crystal may have fronts which are parallel, as *op*, *oq* in Fig. 315; and, conversely, that two beams may travel along the same path OP in the crystal, as in Fig. 316, and yet have fronts q, r, which are not parallel. In this case the beam will give rise on emergence to two diverging beams PQ, PR (compare also Fig. 305).

When the direction of a beam of light, its velocity, the lines along

which the vibrations of its rays are to be regarded as taking place, and the direction of its front are known, the nature of the beam is defined.

All these properties are in the most general case completely expressed by means of either of two ellipsoids, known as the " Fresnel ellipsoid " and the " Indicatrix " respectively.

14. **The Fresnel Ellipsoid.**—We have seen that light traversing a crystal in any direction OP (Fig. 316) emerges in general as two beams of plane-polarised light travelling in two different directions PQ, PR. These two beams result from two coincident plane-polarised beams, which travel along OP with different velocities, and with their wave-fronts inclined, and are therefore differently refracted on emergence. These are polarised at right angles to one another ; and plane-polarised light is, as we have seen above, to be regarded as due to vibrations executed in a single direction ; hence the velocity of the light must vary not only with the direction in which it is travelling, but also with the direction in which its vibrations are executed. In fact it is found that in general each direction within the crystal is the vibration-line of light travelling in a definite direction perpendicular thereto with a certain definite velocity.

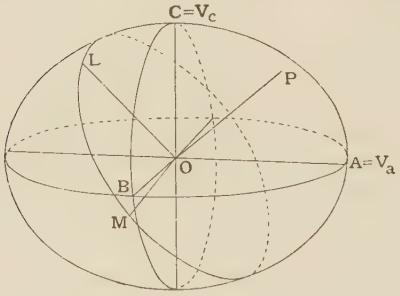


Fig. 317.—The Fresnel Ellipsoid of a (positive) Biaxial Crystal.

In what follows we confine our attention to light of one and the same wave-length : the light, for example, of a sodium flame.

Let O (Fig. 317) be a point of reference arbitrarily selected inside a biaxial crystal. In any direction from O there can travel, in general, two rays of light with different velocities. Let, then, the velocities in all possible directions in the crystal be compared with each other with the object of finding : (1) Those directions in which the light travels with the greatest possible velocity ($= V_a$) ; (2) those in which it travels with the least possible velocity ($= V_c$). It will be found that there are many directions in which a ray travels with the velocity V_a, but that all these lie in one plane. Let this be the plane BOC. Then along any line lying in the plane BOC two rays can be propagated, but the velocity of one of these is constant and equal to V_a, and this ray is polarised in the plane BOC ; it would be absorbed by a tourmaline plate whose axis is held in that plane. The velocity of the other ray varies with its direction.

Draw OA perpendicular to the plane BOC, and of a length proportional to V_a. This line represents the velocity of all rays whose vibrations take place along OA, according to the convention adopted above, namely, that the vibration-direction is to be regarded as perpendicular to the plane in which the light is polarised.

Similarly, if OC be drawn perpendicular to the plane AOB which contains all the rays travelling with the minimum velocity V_c, and of a

length proportional to V_c, then OC represents the velocity of all rays whose vibrations take place along OC. It will further be found that all the rays travelling in the plane AOC, and polarised in that plane, travel with a constant intermediate velocity V_b. Hence OB, drawn perpendicular to the plane AOC and proportional to V_b, represents the velocity of all rays whose vibrations take place along OB.

Thus along OA can travel two rays whose velocities and direction of vibration are represented by OB and OC; along OB can travel two rays represented in the same way by OA and OC; and along OC can travel two rays represented by OA and OB.

Now let an ellipsoid be constructed having OA, OB, OC for its maximum, mean, and minimum semi-axes. This surface, which may be called (from its discoverer) Fresnel's ellipsoid, possesses the following remarkable property.

Take any line OP, and through the centre O draw a plane perpendicular to OP; the plane will cut the ellipsoid in an ellipse; this elliptic section will have two principal axes, a major axis OL, and a minor axis OM, at right angles to one another. Then it is found that the velocity and direction of vibration of the two plane-polarised rays which can travel through the crystal along OP are represented by the length and direction of the lines OL and OM respectively.

The faster of the two rays vibrates along OL and travels with a velocity proportional to OL; the slower vibrates along OM and travels with a velocity proportional to OM. The two rays are further seen from this construction to be polarised in planes perpendicular to each other. Since the two rays which travel along OP are propagated with unequal velocities, they will in general have been differently refracted on entering the crystal, and therefore result from two different rays of the incident light which are not parallel; conversely, also, to any one direction of the incident light there correspond two different rays inside the crystal; or, in other words, light incident on the crystal is, in general, doubly refracted.

The refractive index of the crystal for light vibrating along any one of the three principal axes of the Fresnel ellipsoid being the ratio of the velocity in air to the velocity in the crystal, the refractive index for such light is inversely proportional to the latter; if, then, α is the refractive index for light vibrating along OA, β that for light vibrating along OB, and γ that for light vibrating along OC, OA is proportional to $\frac{1}{\alpha}$, OB to $\frac{1}{\beta}$, and OC to $\frac{1}{\gamma}$, where $\alpha < \beta < \gamma$. α, β, γ are called the three "principal indices of refraction"; α and β belong to the two rays travelling along OC, β and γ to the two rays travelling along OA, γ and α to the two rays travelling along OB.

The mean index β may be taken as a measure of the refractive power of the crystal; the difference $(\gamma - \alpha)$ as a measure of its double refraction or "birefringence."

Beams of light travelling along any of the three directions OA, OB, OC have their fronts perpendicular to the directions in which they are travelling, but it is not so in general with beams travelling in other directions.

15. **The Indicatrix.**—Just as the velocity and direction of vibration for a known *ray* is found from the Fresnel ellipsoid, so may the velocity and direction of vibration for a known *wave-front* be found from another ellipsoid constructed in the following manner upon the same three lines OA, OB, OC, whose directions might be found as described in the last section.

Take OA (Fig. 318) proportional, not to the *velocity* which is constant for the light travelling along different directions in the plane BOC, but to the corresponding *refractive index* (*i.e. inversely* proportional to the velocity); OB proportional to the refractive index which is common to light travelling in the plane AOC; and OC proportional to the index similarly common to light travelling in the plane AOB; so that $OA = \alpha$, $OB = \beta$, $OC = \gamma$, where $\alpha < \beta < \gamma$. Construct an ellipsoid upon these three axes. This ellipsoid, called the "Indicatrix," has the following property.

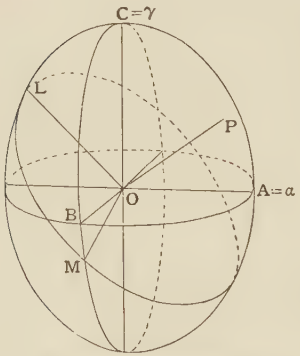


Fig. 318.—The Indicatrix of a (positive) Biaxial Crystal.

Take the elliptic section made by the plane LOM drawn through the centre perpendicular to any line OP; the principal axes OL, OM of this ellipse are proportional to the refractive indices for the two beams of light within the crystal whose *wave-directions* are parallel to OP, that is to say, whose fronts are parallel to the plane LOM.[1]

Further, these two axes lie in the planes containing OP and the vibration-lines of the two plane-polarised beams. Any elliptic section of the indicatrix therefore gives by its axes the refractive indices for the two beams of light whose fronts are parallel to the plane of section, and the planes in which their vibrations take place.

The difference in length of the two axes OL, OM, is a measure of the

[1] The refractive index of an isotropic medium is commonly defined as the ratio:

$$\frac{\text{sine of angle of incidence (in air)}}{\text{sine of angle of refraction}}$$

of the incident and refracted rays, which is equal to the ratio:

$$\frac{\text{velocity of light in air}}{\text{velocity of light in medium}}$$

In a doubly refracting medium it may be seen from the Huygens construction that there is the same equality between the two ratios if the angles of incidence and refraction refer to the *wave-normals*, and the velocities are those of the *waves*, in the direction of their normals. This is not in general true for the directions and velocities of the *rays*.

It is best therefore to define the refractive index of a medium as the ratio:

$$\frac{\text{velocity of } \textit{wave} \text{ in air}}{\text{velocity of } \textit{wave} \text{ in medium}}$$

which will in all cases be equal to the ratio:

$$\frac{\text{sine of angle of incidence of wave-normal in air}}{\text{sine of angle of refraction of wave-normal in medium}}$$

since in an isotropic medium the wave-normal and the ray coincide.

In an isotropic medium the value of these ratios is constant, *i.e.* independent of the angle of incidence; but in a doubly refracting medium this is not so except in the case of the *ordinary* rays.

birefringence of the crystal in the direction OP, that is to say, of the birefringence of the particular section which is cut perpendicular to OP.

It will be seen that the birefringence of plates parallel to the three principal sections of the indicatrix is expressed by $(\beta - \alpha)$, $(\gamma - \beta)$, $(\gamma - \alpha)$, for plates parallel to AOB, BOC, AOC, respectively.

In the Fresnel ellipsoid the axes OA, OB, OC, are in descending order of magnitude ; in the indicatrix they are in ascending order of magnitude ; in the Fresnel ellipsoid they are inversely proportional to the three principal indices of refraction α, β, γ ; in the indicatrix they are directly proportional to these indices $(\alpha < \beta < \gamma)$.

16. **Biaxial Crystals.**—Any plane section of an ellipsoid is an ellipse, and every ellipse has two principal axes, a major axis and a minor axis ;

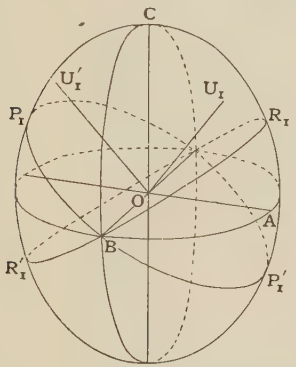


Fig. 319.—The Primary Optic Axes. Circular Sections of the Indicatrix (in a Positive Crystal).

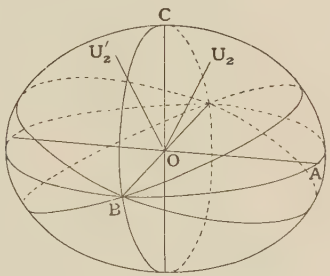


Fig. 320.—The Secondary Optic Axes. Circular Sections of the Fresnel Ellipsoid (in a Positive Crystal).

the section of the indicatrix, for example, by a plane perpendicular to OA, is the ellipse BC, whose major axis is OC, and minor axis OB (Fig. 318).

Now consider successive sections made by a plane, initially coinciding with AOB, as it rotates about OB until it finally comes into the position BOC (Fig. 319) ; each such section is an elliptic curve, but while one axis of the curve, namely OB, remains constant, the other axis is continually increasing in length, from the value OA, which is less than OB, to the value OC, which is greater than OB. Hence some intermediate section, such as P_1BP_1', is an ellipse whose two axes are equal ; in other words, it is a circle.

A line OU_1 drawn from O perpendicular to this circle must lie between OC and OA in the plane AOC ; and evidently there must be a similar circular section R_1BR_1' on the other side of the plane BOC, whose perpendicular OU_1' lies between OC and OA' ; and the angle $U_1OC = U_1'OC$.

Now the radii of the two circular sections are equal (= OB) ; but they represent the refractive index for light whose *wave-front* is perpendicular to OU_1 or OU_1' ; hence light having either of these wave-fronts corresponds

to the refractive index β and must travel with a single velocity inversely proportional to OB; moreover (since a circular section has not two definite axes) the light traversing the crystal with either of these *fronts* will not consist of two definite plane-polarised beams, but may be polarised in any plane.

The two lines perpendicular to the circular sections of the indicatrix are thus unique as being *lines of single wave-velocity*, and are called the "primary optic axes" or the "optic binormals."

In the same way if OU_2 and OU_2' be drawn perpendicular to the circular sections of the Fresnel ellipsoid (Fig. 320), the velocity of any *ray* being given by the axes of the section perpendicular to it, and the section perpendicular to OU_2 being a circle, it is clear that OU_2 is a

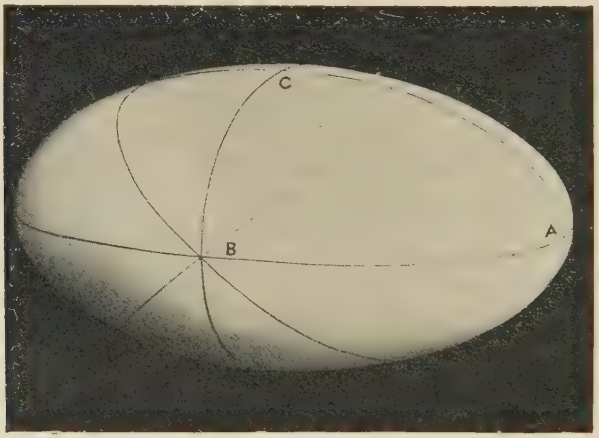


Fig. 321.—Ellipsoid.[1]

direction along which *rays* have only one velocity. The lines OU_2, OU_2', are consequently *lines of single ray-velocity*, and are called the "secondary optic axes," or the "biradials."

Rays travelling along OU_2 do not have two definite planes of polarisation (since the circular section has not two definite axes), but may be polarised in any plane.

The behaviour of light travelling along these directions will be understood by comparing Figs. 323 and 325 with Figs. 315 and 316.

Fig. 323 represents a plate cut perpendicular to a primary optic axis OU_1. A narrow beam of light S, incident perpendicularly on this plate, will give rise in the crystal (not, as usual, to *two* beams, but) to a *hollow cone* of beams (of which two are shown in the figure), whose wave-fronts are all perpendicular to OU_1, and will emerge from the plate as a *hollow*

[1] Fig. 321 may be regarded as representing either the Fresnel ellipsoid of a positive crystal or the indicatrix of a negative crystal, as explained below in Article 24. In the latter case the letters A and C should be interchanged.

cylinder composed of parallel beams. These beams are each plane-polarised and their vibrations are as shown in Fig. 324.

Fig. 325 represents a plate cut perpendicular to a secondary optic axis

Fig. 322.—Circular Section of Ellipsoid.

OU_2. All the beams forming a certain hollow cone SS of incident light travel in this direction through the crystal, though with their wave-fronts inclined to one another, and emerge again as a hollow cone of light whose beams are plane-polarised and vibrate similarly to those in Fig. 324.

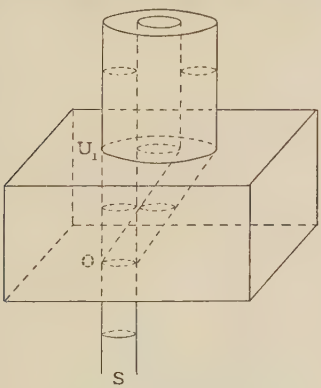


Fig. 323.—Primary Optic Axis or Optic Binormal: Internal Conical Refraction.

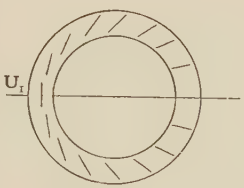


Fig. 324.

These phenomena are described as "internal" and "external conical refraction" respectively (*cf.* p. 160).

Neither OU_1 nor OU_2 can be said to be a line of no double refraction in the exact sense in which this can be said of the optic axis of a uniaxial

crystal like calcite (p. 144). The lines OU_1 most nearly possess this character, and are generally spoken of as "the optic axes" of a biaxial crystal (*cf.* p. 161).

In almost all biaxial minerals the primary and secondary optic axes very nearly coincide, and there is no practical method of distinguishing between them, so that in future we shall be justified in speaking of the lines perpendicular to the circular sections of the indicatrix as "the optic axes." In a crystal of sulphur (p. 348) the angle between a secondary and a primary optic axis is more than $3\frac{1}{2}°$, but this is quite exceptional, and the angle rarely exceeds a few minutes.

17. **Uniaxial Crystals.**—When two of the axes in Fig. 319, say OA and OB, become nearly equal, the circular sections of the indicatrix become nearly horizontal and the two optic axes nearly coincide.

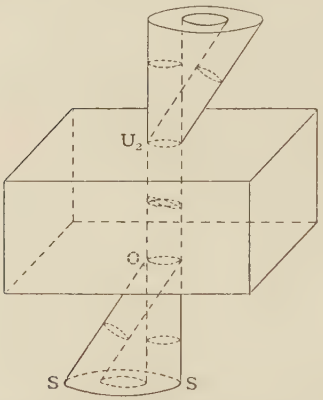


Fig. 325.—Secondary Optic Axis or Optic Biradial: External Conical Refraction.

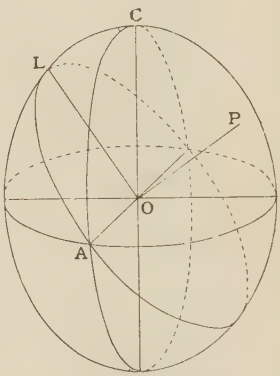


Fig. 326.—The Indicatrix of a (positive) Uniaxial Crystal.

When OA and OB are actually equal, the plane AOB becomes the only circular section, the two optic axes coincide, and the indicatrix becomes a spheroid or "ellipsoid of revolution," such as would be traced out by spinning the ellipse CB about the axis OC.

In the hexagonal and tetragonal systems, by virtue of the symmetry of the system, the axes OA and OB of the indicatrix must be equal, and the two optic axes coincide in the principal axis of the crystal; this line unites in itself the characters of the primary and secondary optic axes, and is a true optic axis or line of no double refraction. Thus hexagonal and tetragonal minerals must be "uniaxial," and their optical characters are derived from an ellipsoid of revolution whose axis of symmetry is the principal axis of the crystal.

The planes of vibration and the refractive indices for the two plane-polarised beams of light whose wave-directions are parallel to any line OP are given by the axes OL, OA, of the ellipse in which a plane perpendicular to OP intersects the indicatrix (Fig. 326). Only along the optic axis OC, which is perpendicular to the circular section, can plane-polarised light be

transmitted polarised in any desired plane and with only one refractive index. In a uniaxial crystal any oblique section (AOL) has for one of its axes the radius OA of the circular section. Hence, of the two beams whose wave-directions are parallel to any line OP, the one which is polarised in the "principal plane" POC, and vibrates at right angles thereto, always corresponds to the same refractive index; so that, as we have seen in the case of calcite, light transmitted obliquely consists in general of an ordinary and an extraordinary beam.

18. **Cubic Crystals.**—In the cubic system, by virtue of the symmetry, all three axes of the indicatrix must be equal, and it becomes a sphere, of which all radii are equal; the section of this sphere by the plane perpendicular to any ray is a circle. In a crystal of this system, accordingly, all rays travel with equal velocity, whatever their direction of vibration, and there is no double refraction. By virtue of their symmetry all cubic crystals must therefore be optically isotropic.

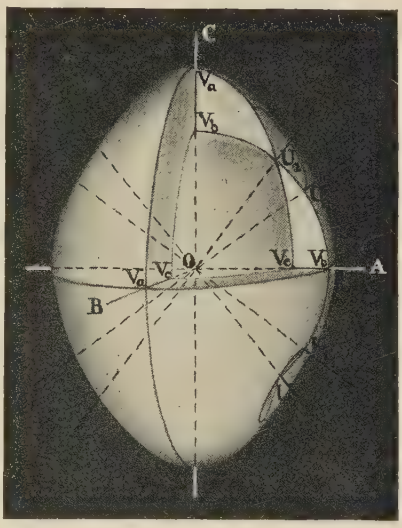


Fig. 327.—Model of the Wave-surface of a Biaxial Crystal.[1]

19. **Construction of the Wave-surface from the Ellipsoids.**—The form of the wave-surface for any crystal may be obtained from the Fresnel ellipsoid by determining the velocities of propagation of rays of light in all possible directions in the crystal by the construction given on p. 153.

A model of the resulting wave-surface for a biaxial crystal is shown in Fig. 327,[1] and the sections of it parallel to the three principal planes AOB, AOC, BOC of the ellipsoid are shown in Fig. 328, in which the lines OA, OB, OC are parallel to the corresponding principal axes of the ellipsoid. Each of these sections consists of a circle, whose radius represents the velocity of ordinary rays with vibrations perpendicular to the plane of the section, and of an ellipse whose radii represent the velocities of extraordinary rays with vibrations executed in that plane. Along each of the lines OA, OB, OC both the rays are ordinary, *i.e.* are perpendicular to their wave-fronts, and their velocities are inversely proportional to two of the principal refractive indices. Thus, along OC, the velocities are represented by $OV_a = \frac{1}{\alpha}$ (vibrations along OA), and $OV_b = \frac{1}{\beta}$ (vibrations along OB);

[1] In this model one octant of the external sheet of the surface has been removed to show the form of the inner sheet and the sections made by the three principal planes. The lettering is the same as in Fig. 328.

and similarly for rays along OA and OB. The two rays propagated in any direction not lying in one of the three principal planes are both extraordinary, *i.e.* inclined to their wave-fronts, and neither of them obeys the ordinary laws of refraction.

The lines OU_1 and OU_2 lying in the plane AOC represent the primary and secondary optic axes respectively. The former are perpendicular to the planes which touch both sheets of the wave-surface and are con-

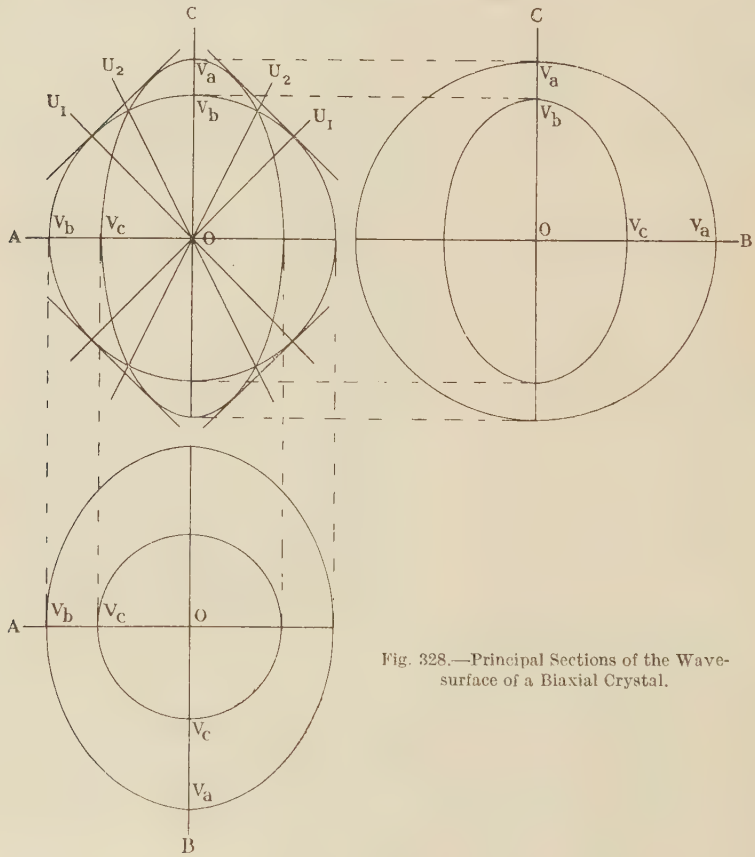


Fig. 328.—Principal Sections of the Wave-surface of a Biaxial Crystal.

sequently the lines of single wave-velocity : the latter pass through the points in which the two sheets intersect, and are the lines of single ray-velocity. Fig. 327 shows that these points lie in small conical depressions in the wave-surface, so that to a single ray OU_2 there correspond an indefinite number of wave-fronts forming this cone, and the refraction of these on emergence from the crystal gives rise to the hollow emergent cone of Fig. 325. The planes perpendicular to the lines OU_1 touch the wave-surface in the small circles seen in Fig. 327 surrounding the

depression, and the rays drawn from O to the points on these circles form the hollow internal cone shown in Fig. 323.

The path of the light in a biaxial crystal is obtained from that of the incident beam by means of the Huygens construction, with the aid of this wave-surface, just as it was determined for a uniaxial crystal in Article 13.

In a uniaxial crystal the wave-surface obtained in the same way has the form of the sphere and spheroid described on p. 150. In any direction, except along the optic axis, there can travel two rays, *viz.* an ordinary ray, whose velocity is represented by the radius of the sphere, and an extraordinary ray, whose velocity is similarly given by the spheroid. The vibrations of the former ray are always perpendicular to the optic axis, while those of the latter are in the plane containing the ray and the optic axis. For a ray travelling along the optic axis there is only one velocity, *viz.* that of the ordinary ray; there is also only one wave-velocity, since both wave-fronts are perpendicular to the ray; and the vibrations may be in any plane. In this direction, therefore, the crystal is singly refracting. The optic axis of the uniaxial crystal combines the properties of the primary and secondary optic axes of the biaxial crystal, since along it there is only a single velocity both for rays and waves.

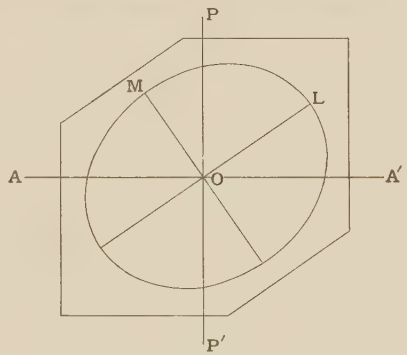


Fig. 329.—Extinction-lines of a Section.

In cubic crystals the wave-surface is spherical and the crystal is singly refracting in all directions.

The form of the wave-surface of a crystal can also be derived, by a slightly different construction, from its indicatrix. In the remainder of this book the indicatrix alone will be used.

20. **Extinction.**—We have seen that when a slice cut out of any doubly refracting crystal is examined with parallel light between crossed nicols, there are in general four positions in which the section becomes dark as the stage is rotated. This is easily explained by means of the indicatrix.

The intersection of the indicatrix with the plane of the slice is an ellipse whose axes represent the vibration-planes of the light incident on the plate perpendicularly, and whose wave-front is parallel to the surface of the plate.

Let Fig. 329 represent a crystal plate lying on the stage between the polariser, whose vibration-direction is PP′, and the analyser, whose vibration-direction is AA′. Let the ellipse, whose axes are OL, OM, be the intersection of the plate with the indicatrix of the crystal. Plane-polarised light issuing from the polariser enters the crystal vibrating in the plane OP. If OP does not coincide with OL or OM, the incident rays give rise in the crystal to rays vibrating in the planes OL and

OM respectively. Each of these vibrations has a component along OA, so that some light from each is transmitted by the analyser.

If, however, the crystal is so placed that either OL or OM is parallel to OP, the plane-polarised vibrations pass unchanged through the crystal, and are extinguished by the analyser.

The four positions in which the section becomes dark are therefore those in which its vibration-planes coincide with the vibration-planes (or shorter diagonals) of the nicols. These positions are called the " positions of extinction."

The lines OL, OM may be called the " extinction-lines " of the crystal section. Every section which shows double refraction must therefore have two characteristic extinction-lines at right angles to each other, and corresponding positions of extinction on the microscope stage.

A very important process in the optical identification of a mineral consists in finding the extinction-lines for different faces.

The angle made by one of the extinction-lines of any face with a definite edge of the crystal is called the " extinction-angle of the face." Thus the extinction-lines of a crystal of diopside from Nordmark in Sweden when examined normally through different pairs of parallel faces are represented in Fig. 330. Through a pair of prism-faces the angle which one of these lines makes with the prism edge is 36°; and this is said to be the " extinction-angle " of the prism-face of this diopside; the extinction-angle on the clino-pinakoid (010) is not the same but 46° 45′. The extinction-angle of any section of a crystal is found in the following way.

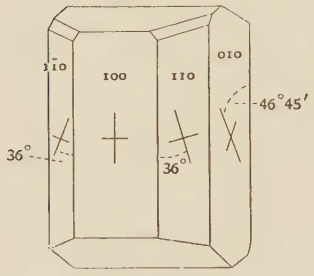


Fig. 330.—Extinction-angles of Diopside.

The crystal is laid flat upon a glass slide on the stage of the microscope, resting upon one of the two parallel faces under examination. The eyepiece of the microscope contains a pair of cross-wires so fixed as to be parallel to the vibration-planes (*i.e.* the shorter diagonals) of the polariser and analyser; parallel light being used, the stage is first turned until the required edge is parallel to one of the cross-wires, and a reading is taken on the graduated circle. The stage is then turned until the crystal appears uniformly dark. In the first position the cross-wire is parallel to the edge of reference; in the second position it is parallel to one of the extinction-lines of the section. The angle through which the stage has been turned is the extinction-angle of the section with reference to that edge. When an extinction-line is parallel to the edge of reference, the section is said to have " straight extinction " with regard to that edge. The face (100) in Fig. 330 has straight extinction.

When a face or section is parallel to a principal axis of the indicatrix, its extinction is also parallel to that axis; for when a plane section of the indicatrix passes through one of its axes, that axis is either the major or the minor axis of the elliptic section.

In the hexagonal, tetragonal and orthorhombic systems, one of the axes of the indicatrix always coincides with the vertical axis of symmetry of the crystal. Hence a prism-face in any of these three systems has straight extinction.

The following is a very useful construction which enables the extinction-lines on any given face of a crystal to be obtained when the directions of the optic axes are known.

In an ellipsoid, to find the axes of any elliptic section OLM (Fig. 331), draw two planes through the line OP perpendicular to the section, one containing the optic axis OU, the other containing the optic axis OU′. Draw through the normal two other planes OLP, OMP bisecting the angles of the first pair, and therefore at right angles to each other; they will cut the elliptic section in its two axes, OL, OM.

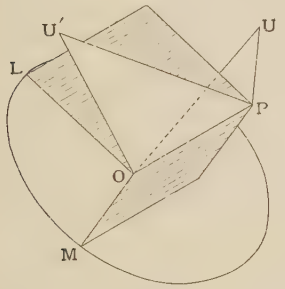


Fig. 331.—Extinction-lines and Optic Axes.

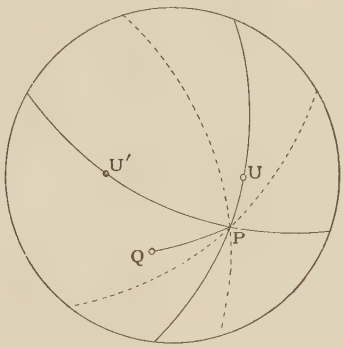


Fig. 332.—Extinction-angles and Optic Axes.

Hence the extinction-lines on any face or section are found by the same construction—made as follows on the stereographic projection.[1]

Let P be the pole of the face or section—let U, U′ be the points on the sphere where the optic axes emerge (Fig. 332). Bisect the angle UPU′ internally and externally by planes which cut the sphere in the dotted circles (see p. 33); then these planes contain the extinction-lines. Let Q be the pole of another face; then the extinction-angle of P, taking the edge PQ as edge of reference, is the angle between one of the dotted circles and the arc PQ. From this construction it follows that in a uniaxial crystal, since U and U′ coincide, one of the extinction-lines must always lie in the plane containing the optic axis and the normal to the section. This plane is called a "principal plane" of the crystal.

In accordance with this principle each face of the calcite rhombohedron of Fig. 300 must have extinctions parallel to its diagonals; for the shorter diagonal ZE lies in the principal plane, and the longer diagonal MN is perpendicular to it; for this reason also the images *o* and *e* were

[1] In a stereographic projection the angles between intersecting great circles in the projection are the same as those between the planes of the corresponding circles on the sphere, and hence the angles between these planes can be measured directly on the projection.

extinguished by the tourmaline plate when its axis was in the principal plane or perpendicular to it, respectively.

21. **Interference-phenomena seen in Parallel Light.** — We have seen that in general a section when viewed in white light between crossed nicols, if not in a position of extinction, appears coloured, and that this colour varies with the thickness of the section.

We have now to consider the cause of these phenomena.

In the production of interference by the reflection of light from thin films, as in Newton's rings, the phase-difference between the two interfering rays is produced by causing these to traverse paths of different length. A similar phase-difference might also be produced by causing the two rays to traverse a certain portion of their path with different velocities, so that one would lag behind the other. This is precisely what happens in the passage of light through a crystal.[1]

When a ray of monochromatic light, of wave-length λ (in air), enters

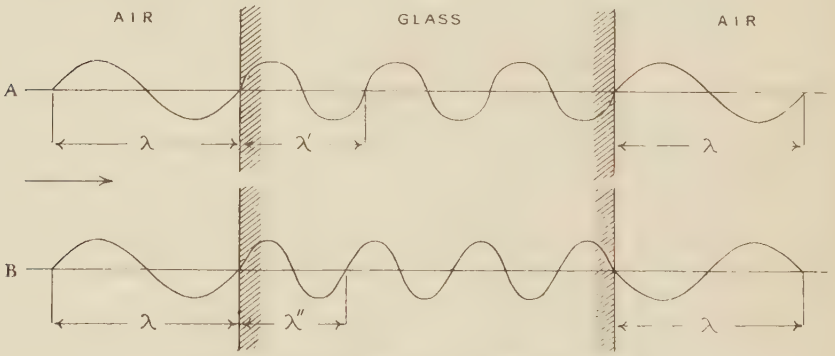


Fig. 333.—Passage of Light through a Retarding Medium.

a plate of a transparent substance such as glass perpendicularly, its velocity is diminished. If N be the frequency, or the number of vibrations executed per second, corresponding to the particular colour, and the velocity of light in air be V, then $V = N\lambda$. The diminution of velocity on entering the glass must be due to a diminution of the wave-length (as at A, Fig. 333), since passage into the glass can have no effect on the frequency of the vibrations. Thus, if the velocity in glass be V′, and the corresponding wave-length λ', $V' = N\lambda'$. If the velocity were reduced to V″, the wave-length would be proportionately diminished to λ'', as at B, Fig. 333. The effect of the difference of velocity would be to cause the ray B to lag behind A, and an increasing difference of phase would be produced, which in the figure amounts to $\frac{\lambda}{2}$ when the original wave-length is restored on emergence into air.

[1] It is true that the velocity of light in a thin film is different from that in the surrounding medium; it may be either greater (Newton's rings) or less (soap film), but its effect is less important than that of the length of path. In a crystal the difference of path is small and the chief cause of the phase-difference is the difference of velocity.

Consider a section of a uniaxial mineral cut obliquely to the optic axis. When a beam of monochromatic light, such as the light from a sodium flame, enters the plate normally, as at R, Fig. 334, it is doubly refracted ; the ordinary beam continues its course unchanged through the section, since the incidence is perpendicular ; the extraordinary beam is refracted, but on issuing from the section recovers its original direction, since the faces of the plate are parallel. The ordinary and extraordinary beams will consequently be parallel after emergence, and the extraordinary beam E, which entered the plate at R, will follow the same path as the ordinary beam O_1, which entered at R_1. Both the ordinary and extraordinary beams will have been retarded in traversing the section, but to a different extent, so that one will have lagged behind the other : hence E and O_1 will no longer be in the same phase and would be in a

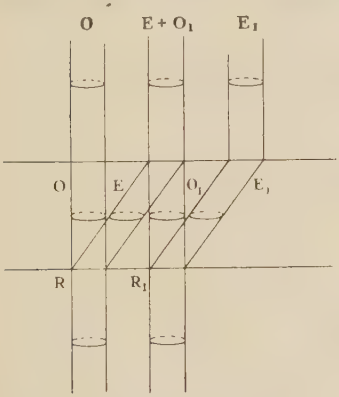


Fig. 334.—Oblique Section of a Uniaxial Crystal.

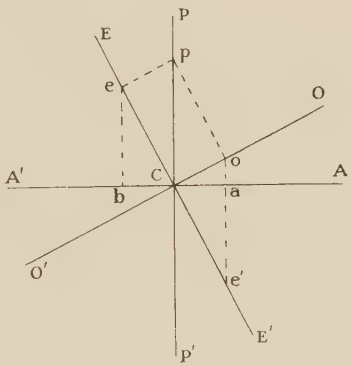


Fig. 335.

condition to interfere were it not that they are vibrating in two planes at right angles to each other.

Consider next what will happen when the section is placed between crossed nicols. In Fig. 335 let a beam of light from the polariser emerge at C perpendicularly to the paper, having its vibrations along PP' ; and let the section be placed so that the directions of vibration of the ordinary and extraordinary beams are OO' and EE' respectively. The direction of vibration of the analyser will be AA'. The light incident on the section from the polariser, whose vibrations are represented in direction and semi-amplitude by C*p*, is resolved in the crystal into two simultaneous vibrations represented by C*o* and C*e*, and after emerging from the crystal each of these will have a component along AA' which is transmitted by the analyser (*viz.* C*a* and C*b*), and these components will interfere.

If the two beams emerge from the section in the same relative phase as that in which they entered, *i.e.* if their relative retardation has been zero or any whole number of wave-lengths ($=n\lambda$), the vibrations C*o* and C*e* will be simultaneous, and their components along AA', *viz.* C*a* and C*b*,

will be in opposite directions, and, being equal in amplitude, they will neutralise one another, and the section will appear dark although not in the position of extinction. If, however, one beam has undergone half a wave-length more retardation than the other, like those shown at A and B in Fig. 333, the simultaneous displacements will be represented by Co and Ce' instead of Co and Ce. The component of each of these along AA′ is Ca; their resultant will be $2 \times Ca$, and the section will appear bright.

If a section which gives a relative retardation of $n\lambda$ for yellow light be examined in white light, which is composed of lights of different wave-lengths, the yellow will be destroyed by interference and the colour seen will be that "complementary" to yellow, which consists of the remaining colours of the spectrum and is of a purplish tint.

If the section be wedge-shaped (Fig. 336), *i.e.* of gradually increasing thickness from one end to the other, like the wedge of quartz described on p. 194, in yellow light it will appear bright except at those points where the thickness is just sufficient to cause a relative retardation of λ, 2λ, 3λ, . . . $n\lambda$, and will therefore be crossed by a number of equidistant dark bands (Fig. 337).

If blue light be substituted for yellow, a less thickness of crystal will

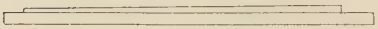


Fig. 336.—Quartz Wedge on a Glass Slip, Side View.

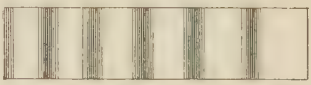


Fig. 337.—Quartz Wedge viewed in Parallel Light between Crossed Nicols.

be required to give the necessary relative retardation for any given band, and the bands will be closer together.

If white light be used a series of coloured bands will be obtained, whose colours closely resemble those of Newton's rings, as described on p. 136.

The amount of relative retardation produced by a given section, and consequently the colour which the section will show in white light between crossed nicols, depends not only upon the thickness of the section, but also on the difference of velocity of the two beams, *i.e.* upon the difference between the two refractive indices or the strength of the double refraction.

Many minerals may be distinguished from each other by these tints alone; thus in rock sections of the usual thickness (about 0·04 mm.) quartz, being a mineral of weak double refraction, "polarises" in the lower colours of the first order; olivine, having moderately strong double refraction, polarises in the brilliant colours of the third order; while calcite, a mineral of very strong double refraction, polarises in the "white of higher orders."

Since the colour varies with the strength of the double refraction, and the double refraction of a section depends upon its direction in the crystal, sections of the same thickness cut from crystals of the same mineral in different directions (as in a rock-section) will also present different colours between crossed nicols, the highest colours being given

by a section parallel to the optic axis of a uniaxial or to the two optic axes of a biaxial mineral.

22. **Interference Phenomena in "Convergent Light."**—Consider first a plate cut from a uniaxial crystal perpendicular to the optic axis. The indicatrix is here an ellipsoid of rotation, and all sections inclined at the same angle to the principal axis are similar ellipses; all such sections will show the same double refraction. The double refraction continually diminishes from the direction perpendicular to the principal axis, where it is a maximum, to that parallel to the principal axis, along which there is no double refraction; for in the latter case the axes of the corresponding section of the indicatrix are equal, while in the former they are as widely different as possible.

Let the adjoining figure (Fig. 338) represent a side view of the crystal (which may be either hexagonal or tetragonal); then OC, the vertical

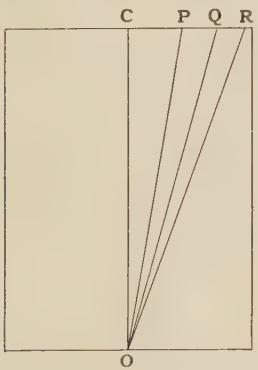


Fig. 338.—Interference in a Uniaxial Crystal.

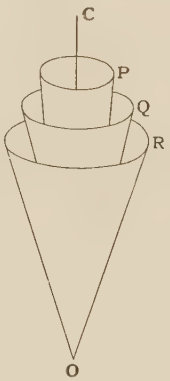


Fig. 339.—Interference in a Uniaxial Crystal.

axis, is also the optic axis. OP may be a direction in which for a plate of the given thickness the relative retardation for sodium light is λ; then all other directions with the same inclination to OC will also correspond to a relative retardation λ_{Na}.

Similarly all directions inclined to OC at the angle COQ may correspond to a relative retardation 2λ; and those inclined like CR correspond to 3λ, and so on. In passing from OP to OQ the relative retardation has been increased, partly owing to the greater double refraction along OQ and partly to the longer path traversed by the more oblique rays in the crystal plate.

In all such directions there will be darkness, and in all intermediate directions there will be light, when the plate is examined in convergent sodium light between crossed nicols (see p. 147).

Each set of directions forms a cone with circular base surrounding the optic axis (Fig. 339). The first cone represents all the directions in the crystal along which the birefringence is such as to produce, in the given plate, a relative retardation of λ; the second, 2λ; and so on.

For any other light or for any other thickness of plate the directions corresponding to relative retardation of λ, 2λ, etc., are also represented by circular cones about OC, but they will have a larger or smaller angle than those through OP or OQ of Fig. 339. The thicker the section the smaller will be the angle of the corresponding cone.

If white light be used each cone represents directions along which light of a certain wave-length (or certain wave-lengths) is annulled, and therefore mixed light of the complementary, or residual, colour is transmitted. A section of given thickness, cut perpendicular to any line such as OP in one of these cones, will have the same colour when examined in white light between crossed nicols as a section of the same thickness cut perpendicular to any other line through O in the same cone.

Each cone shows the directions along which the double refraction is the same, and therefore also those in which the interference-colours produced in convergent white light by a plate cut perpendicular to the optic axis are the same.

For biaxial crystals the same considerations hold true (Fig. 340).

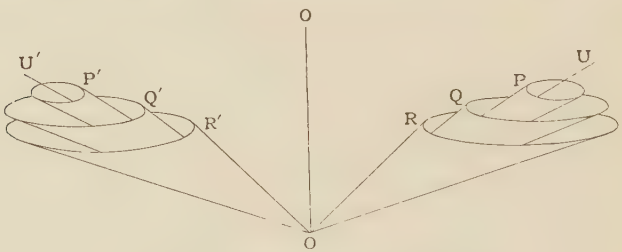


Fig. 340.—Interference in a Biaxial Crystal.

Directions along which the birefringence is very weak will nearly coincide with the optic axes U,U′, but the cone containing directions whose birefringence is the same will be (by virtue of the lower symmetry of the crystal) no longer circular. In a plate of given thickness perpendicular to the line OO which bisects the angle between the two optic axes, the directions along which the birefringence and length of path in the crystal are such as to produce a relative retardation of λ for a given colour, say sodium light, will lie on a pair of oval cones, P and P′, surrounding the two optic axes; and each of these will be surrounded by larger cones Q, Q′, etc., containing the lines along which (for the same plate of crystal) the relative retardation produced is respectively 2λ, 3λ, etc.

The birefringence along each line is measured by the difference between the axes of the indicatrix-section perpendicular to it.

The use of "convergent light" makes it possible to observe simultaneously the interference-effects due to light travelling in many different directions through one and the same section. The mode of formation of an "interference-figure" is indicated in Figs. 341 and 342. The section AB is placed on the stage of the microscope between the condenser and a high-power objective. The light from the condenser reaches the crystal

at different angles, and those rays which traverse it as a parallel beam, parallel to the axis of the microscope (Fig. 341), are brought to a focus at C in the centre of the field, in the principal focal plane of the objective. All the parallel rays travelling through the crystal at a given inclination COp to the axis of the microscope OC are brought to a focus at a point p situated at a certain distance from C (Fig. 342). A beam of rays more inclined to the line OC converges to a point at a greater distance from C. Between crossed nicols, the result is therefore to form a luminous pattern, the "interference-figure," every different point of which is produced by the interference of rays which have traversed the crystal in a certain different direction. This effect may be seen, as stated on p. 147, either by removing the eyepiece or by introducing a lens at an appropriate distance above the objective (the "Bertrand lens," which forms an image of the figure in the eyepiece) or above the eyepiece.[1]

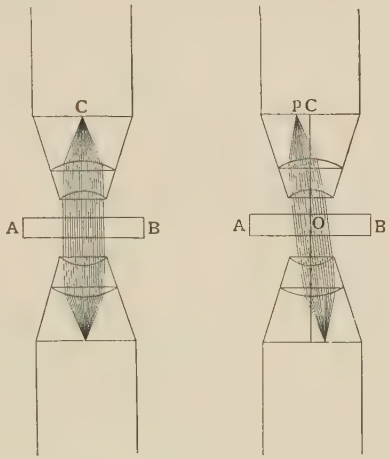


Fig. 341. Fig. 342.
Formation of an Interference-figure.

In a slice cut perpendicular to the optic axis of a uniaxial crystal, the centre of the field of view will correspond to all the rays of light travelling along the optic axis, and will be a dark spot denoting a direction of no double refraction. In sodium light this will be surrounded by a dark circular ring corresponding to the cone of rays P of Fig. 339 (relative retardation $= \lambda$), and this again by a series of concentric dark rings, corresponding to the cones Q, R, etc. (relative retardation $= 2\lambda, 3\lambda$, etc.), the intermediate annular spaces being bright. In white light the rings will be coloured like the bands of the quartz wedge and pass outwards into the white of higher order. Hence the interference-figure seen in convergent light through this section will have the form of the curves in which the plane of the section cuts the cones of Fig. 339. The closeness of the rings will vary with the thickness of the section and the strength of the double refraction of the crystal, conjointly.

It was stated above that the circles of the uniaxial interference-figure are intersected by a black cross; we have next to explain this feature.

Consider any point R in Fig. 343 not lying on AA′ or PP′. This point corresponds to two rays inclined to the optic axis in the "principal plane" through RO, one vibrating in that plane, the other perpendicularly to it. These have each a component along OA, and after

[1] The term "convergent" is rather misleading, since it is the rays which have traversed the crystal as a *parallel* beam which produce the colour at any point in the field.

traversing the analyser these two component vibrations interfere and produce the colour corresponding to the cone through R.

Now consider the light corresponding to any point L on PP′. This travels through the crystal as a plane-polarised ray vibrating in this principal plane (see p. 163), for it has no component perpendicular thereto, and it is therefore extinguished by the analyser; consequently any such point lying on the line PP′ is one of darkness. Similarly the ray corresponding to M has no component along OA; it passes through the crystal, vibrating along OP alone, and is extinguished by the analyser; and this is true of any ray lying in the plane OM. Hence the lines PP′ and AA′, parallel to the vibration-directions of the polariser and analyser in the microscope, become the two arms of a black cross intersecting the circles of the uniaxial interference-figure (see Fig. 376, p. 193).

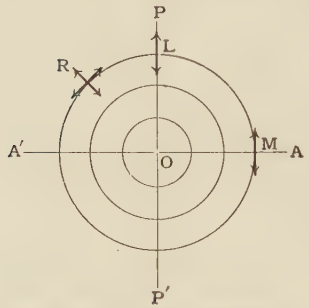


Fig. 343.—Uniaxial Interference-figure.

In biaxial crystals the general form of the interference-figures is indicated by the cones of equal relative retardation of Fig. 340, just as those of uniaxial crystals were suggested by Fig. 339.

Fig. 344.—Biaxial Interference-figure Diagonal Position. Relative Retardation 3 Wave-lengths.

A section perpendicular to the line OO of Fig. 340 will exhibit two dark spots u,u', Fig. 345, corresponding to the optic axes, and these will be surrounded, in sodium light, by dark and bright oval rings. The first few rings will generally form pairs of ovals surrounding the

optic axes; a later pair may join at the centre in a curve, known as a lemniscate, resembling a figure of 8 (Fig. 344), and the subsequent rings

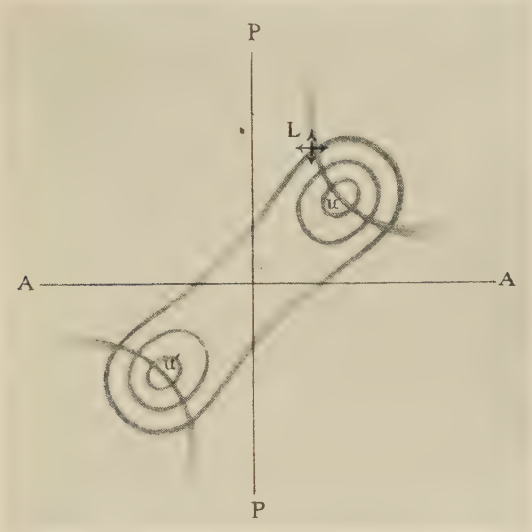


Fig. 345.—Relative Retardation 2½ Wave-lengths.

will form continuous curves. In white light the rings are coloured as in a uniaxial crystal, and pass outwards into the white of higher orders.

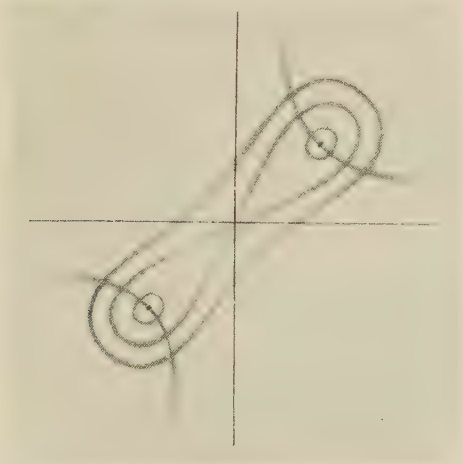


Fig. 346.—Relative Retardation 2 Wave-lengths.

The effect of reducing the thickness of a section may easily be observed by cleaving a plate of mica successively into thinner and

thinner sheets, and is shown in Figs. 344-348, which represent the interference-figures seen in monochromatic light as the relative retardation in the centre of the field is reduced from three wave-lengths to half a wave-length.

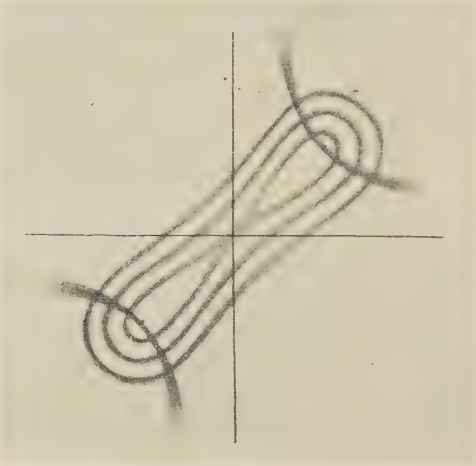


Fig. 347.—Relative Retardation 1 Wave-length.

As in a uniaxial, so also in a biaxial crystal the rays must be more inclined to an optic axis in order to produce a given relative retardation

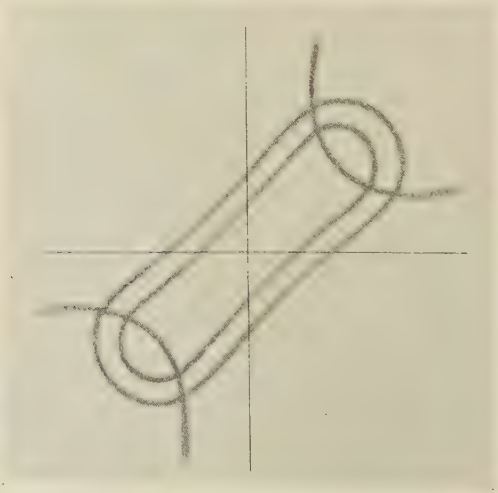


Fig. 348.—Relative Retardation ½ Wave-length.

in a thin section than in a thicker one, and the rings are consequently larger.

An optic axis will no longer be intersected by a black cross. There

are, however, certain dark bands or "brushes" which correspond to the black cross of the uniaxial figure. The crystal being turned through 45° from the position of extinction, for some point L in the figure the directions of vibration (found, as described above, by bisecting the angles between two planes containing the ray L and the optic axes) may prove to be parallel to PP′ and AA′ (Fig. 345). Wherever this is the case darkness will result, for the same reason as at the point L in Fig. 343. The total assemblage of such points constitutes the two branches of a hyperbola, one of which passes through each of the two optic axes, *u,u′*. If the section is rotated with the stage, the optic axes rotate with the crystal round the centre, the rings retaining their form; but the dark "brushes"

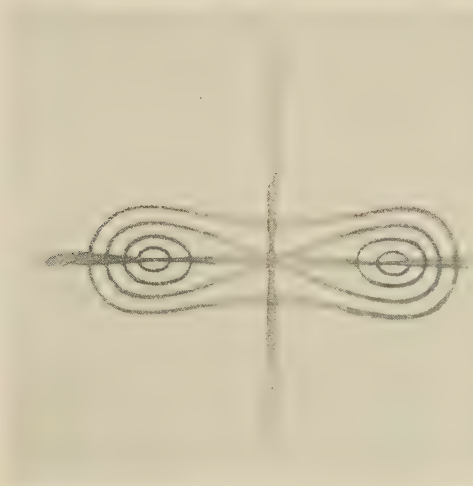


Fig. 349.—Biaxial Interference-figure; Extinction-position. Relative Retardation 3 Wave-lengths.

swing round and unite to form a cross when the crystal has reached the extinction-position. Thus the interference-figure of Fig. 344 changes to that of Fig. 349. In the latter position (extinction-position) the plane of the optic axes coincides either with PP′ or AA′. The former position, where the plane of the optic axes is inclined at 45° to AA′ and PP′, and the brushes form the two branches of a hyperbola, is called the "diagonal position."

23. **The Axial Angle. The Bisectrices.**—The optic axes in a biaxial crystal are inclined to one another at some angle which is called the "optic axial angle." As observed in air by the microscope, the optic axes appear to include a considerably larger angle, since light travelling along them is refracted out of the crystal with a greater divergence, as shown in Fig. 350.

The angle between the two lines U,U′ is called the "true axial angle"; it is the angle between the optic axes inside the crystal, and is

represented by the symbol 2V; but the distance apart of the two axes as observed in the microscope corresponds to the angle between the lines u and u' as refracted outside the crystal; this is called the "apparent axial angle in air," and is denoted by the symbol 2E. Since the refractive index for light travelling along an optic axis is β, $\sin E = \beta . \sin V$.

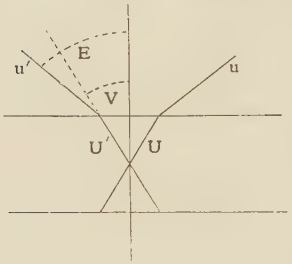


Fig. 350.—Apparent Axial Angle.

The apparent axial angle may be conveniently and approximately estimated by means of a micrometer placed in the eyepiece; each mark on the micrometer corresponds to rays of a certain obliquity, and the apparent angle may therefore be estimated by the number of divisions between the optic axes. The micrometer may be calibrated by means of crystals with known axial angles. The manner in which the optic axial angle can be accurately measured is described on p. 199.

The section has been hitherto supposed to be cut perpendicular to the line bisecting the acute angle of the optic axes; if it be cut perpendicular to the line bisecting the obtuse angle, a portion of the ring system may be visible, as may be seen from a consideration of Fig. 340 (in which the vertical line bisects the obtuse angle UOU'), but the rays corresponding to the optic axes themselves are now so widely divergent that in general they either are totally reflected within the section, or are refracted out at an apparent angle so large that it exceeds the limits of the field of view.

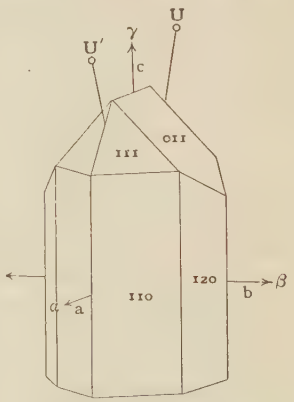


Fig. 351.—The Optic Axes of Topaz.

Of the three axes of the indicatrix for a given colour, one must coincide with the line bisecting the acute angle of the optic axes; this is called the "acute bisectrix" or the "first mean line." A second axis bisects the obtuse angle between the optic axes, and is called the "obtuse bisectrix" or "second mean line." The third, which must always be the mean axis OB, the vibration-direction of light corresponding to the index of refraction β, is perpendicular to the plane of the optic axes, and is called the "third mean line." Fig. 351 represents these lines in a crystal of topaz, in which the vertical crystal-axis c is the acute, and the axis a the obtuse bisectrix.

It is evident that the optic axes will generally be visible through a section cut perpendicular to the acute bisectrix. The central portion of a ring system, not including the optic axes, may be visible in a section cut perpendicular to the obtuse bisectrix, while neither optic axes nor ring system will be visible (in white light) in a section cut perpendicular to the third mean line.

When the section is perpendicular to the obtuse bisectrix, although the optic axes may not be visible, the hyperbolic brushes will be seen to enter the field symmetrically, to meet in a cross *at the centre of the field*, and to separate again symmetrically, as the stage is rotated. This will not be the case with a section cut obliquely to a mean line.

Even when the optic axis of a uniaxial, or the two optic axes of a biaxial, crystal are not completely visible, their position may be approximately determined from the portion of the interference-figure which falls within the field of view.

The accompanying diagrams (Figs. 352, 353) show the manner in which portions of the interference-figure may be visible, and may enable the observer to construct the remainder of the figures, as indicated outside the circle which represents the field of view of the microscope.

The optic axis of a uniaxial crystal may always be distinguished from

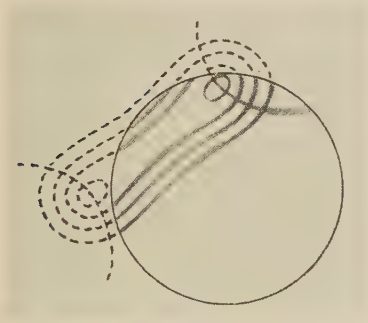


Fig. 352.

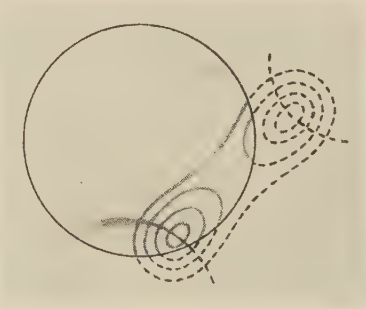


Fig. 353.

Interference-figures of Sections cut obliquely to the Acute Bisectrix.

an axis of a biaxial crystal, since the former is intersected by the *two* arms of a black cross, the latter by only *one* branch of the hyperbola.

24. **Sign of the Birefringence.**—In a uniaxial crystal the optic axis may be either the major or the minor axis of the indicatrix; in the first case the indicatrix is a prolate spheroid, resembling an egg; in the second it is an oblate spheroid, resembling an orange. Similarly in a biaxial crystal the acute bisectrix may be either the greatest or the least axis of the indicatrix.

Fig. 326 represents the indicatrix of a uniaxial crystal in which OC, the optic axis, is the major axis; then light whose wave-direction is OP consists of two sets of waves vibrating in the planes AOP and LOP. Of these two, whatever may be the direction of OP, one always vibrates along a radius of the spheroid equal to OA; all such waves travel with the same velocity and are equally refracted; they therefore correspond to the ordinary rays. OA then is the ordinary index of refraction, and OL the extraordinary index for the light whose direction is OP.

Now OA is a minor axis of the spheroid. OL is therefore greater than OA, and any extraordinary index of refraction in such a crystal is always

greater than the ordinary index, the greatest being the "principal extraordinary index" corresponding to vibrations along OC.

Such a crystal is said to have "positive birefringence." Its optic axis is the vibration-direction of light corresponding to the greatest possible refractive index in the crystal, *i.e.* to the minimum velocity.

In other uniaxial crystals the optic axis may be the vibration-direction for the least possible refractive index, and maximum velocity, and any extraordinary index is therefore less than the ordinary. Such crystals are said to have "negative birefringence."

Using the symbol ω for the ordinary and ϵ for the principal extraordinary index of refraction, the sign of the birefringence is that of the quantity $(\epsilon - \omega)$. In a positive crystal, like quartz, the extraordinary index is greater than the ordinary. In a negative crystal, like calcite, the extraordinary index is less than the ordinary.

The forms of wave-surface corresponding to positive and negative birefringence in uniaxial crystals are shown in Figs. 311 and 312 respectively.

By analogy, the same terms are used to distinguish between the two sorts of biaxial crystals. The indicatrix of a biaxial crystal in which the intermediate refractive index β is nearly equal to α resembles that of a positive uniaxial crystal, and such crystals are therefore called positive. When β is nearly equal to γ, the indicatrix resembles that of a negative uniaxial crystal, and the crystal is said to be negative.

It follows from the relation which exists between the principal refractive indices and the optic axial angle (see p. 202), that in the former case the acute bisectrix is the greatest axis of the indicatrix, *i.e.* the vibration-direction of light corresponding to the refractive index γ. In the latter case the acute bisectrix is the least axis of the indicatrix, or the vibration-direction corresponding to the refractive index α.

The least axis of the indicatrix (α) is frequently described as the "negative bisectrix" (whether acute or obtuse), and the greatest axis (γ) as the "positive bisectrix."

The manner in which the sign of a crystal is determined practically is described on p. 191.

It sometimes happens that a section can be seen from its interference-figure to be perpendicular to a bisectrix, but it is not known whether it is the acute or the obtuse bisectrix; it is only certain that the third mean line must lie in the plane of the section. In such a case, however, if the perpendicular to the section is a radius of the indicatrix which is greater than the third mean line, it is known to be a *positive bisectrix*; if it is less than the third mean line it is known to be a *negative bisectrix*.

25. **Dispersions of the Optic Axes and Bisectrices.**—The indicatrix for light of one colour in any crystal is not the same as that for light of another colour; hence the optic axes of a biaxial crystal may have different positions for different colours. This is known as the "dispersion of the optic axes." Yet, owing to the cardinal principle that the geometrical symmetry-planes and -axes of a crystal are also planes and axes of symmetry for the physical characters (p. 120), the dispersions in the three biaxial systems are of different sorts.

Orthorhombic System.—Here the three axes of symmetry of the indicatrix must coincide with those of the crystal, whatever the colour of the light, and therefore the axes of the indicatrix must coincide with the axes of the crystal. Hence, for all colours, one crystal-axis must be the acute bisectrix, a second the obtuse bisectrix, and the third must be the third mean line. On the other hand, the positions of the optic axes may vary, so long as they lie in the planes of symmetry and are inclined symmetrically to them; but the axial angle for one colour may be larger than the axial angle for another colour.

When the axial angle for red light is greater than that for blue light, the interference-figure seen by monochromatic red light (*e.g.* a flame coloured by lithium) may be that indicated by the continuous lines in Fig. 354, while the figure in monochromatic blue light occupies the position of the dotted lines. S and S′ are the two symmetry-planes of the crystal. The interval RR′ is greater than BB′, corresponding to a larger axial angle.

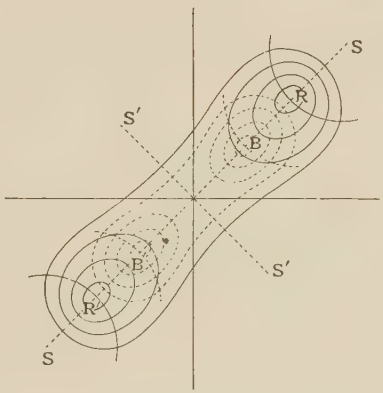


Fig. 354.—Dispersion of the Optic Axes.

In white light the figure will be that resulting from the superposition of all such monochromatic figures. The hyperbolic brush will on the whole occupy the region between B and R, but will be fringed with colour; at the point B, where the blue light is extinguished, it will be reddish; at the point R, where the red light is extinguished, it will be bluish. Hence when the axial angle for red is greater than that for blue, the brush will appear red on its convex, and blue on its concave side in the neighbourhood of the optic axes; *i.e.* the red portions will lie closer together than the blue portions.

On the other hand, when the axial angle for red is less than that for blue, the effect is reversed; red light is extinguished at two points which are closer together than those at which blue light is extinguished. The hyperbolic brushes are blue on their convex, and red on their concave side.

When the axial angle for red is greater than that for blue the character is expressed thus, $\rho > v$; when the axial angle for red is less than that for blue it is written $\rho < v$.

There is one other mode of dispersion possible in the orthorhombic system. One crystal-axis, for example a in Fig. 355, may be the acute bisectrix for all colours, but the optic axes for *red* may lie in one symmetry-plane, *e.g.* (001), while the optic axes for *blue* lie in the other symmetry-plane, (010). This does not violate the symmetry of the system. In this case, if lights of different colours in the order of increasing wave-length are successively employed, the interference-figure changes. With monochromatic blue light the optic axes emerge at BB as shown by the dotted

lines of Fig. 356 ; with red light at RR, as shown by the continuous lines ; and as light of gradually increasing wave-length is employed, the optic axes close up to the bisectrix along BB and then open out at right angles to this, along the line RR. For some intermediate colour, such as green,

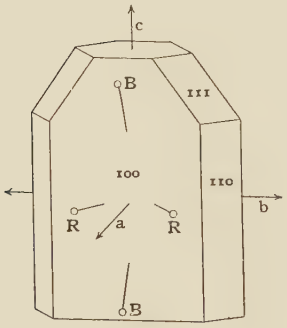


Fig. 355.—Crossing of the Optic Axial Planes in Brookite.

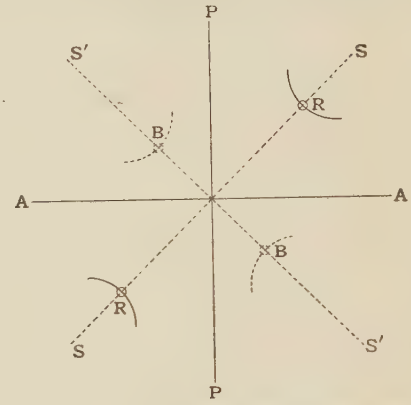


Fig. 356.—The Interference-figures of Brookite in Red and Blue Light.

the crystal is uniaxial. But it is easily distinguished from crystals belonging to the hexagonal or tetragonal systems, since these are uniaxial for *all* colours.

This mode of dispersion is remarkably exemplified by the mineral brookite, diagrammatically represented in Fig. 355. Such a mineral is said to have the "planes of its optic axes crossed."

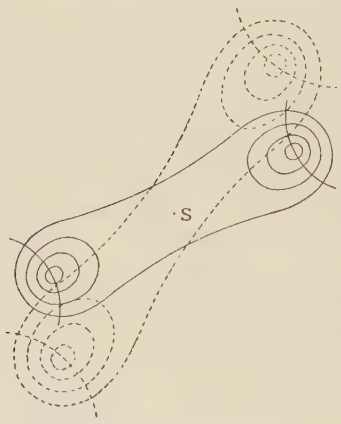


Fig. 357.—Crossed Dispersion.

The essential and characteristic feature of the interference-figures of all orthorhombic crystals is their symmetry about the two lines SS and S′S′.

Monoclinic System.—Here, in addition to the dispersion of the optic axes, the crystal may also present a "dispersion" of one or both of the bisectrices ; for it is no longer necessary that they should both coincide with crystal-axes, but the bisectrices for different colours may occupy different positions. The plane of symmetry must coincide with one of the principal planes of the indicatrix ; in other words, the axis of symmetry, *i.e.* the crystal-axis *b*, must coincide with one of the axes of the ellipsoid. The three possible cases are those in which the *b*-axis coincides respectively with the acute bisectrix, the obtuse bisectrix, and the third mean line.

(1) *Axis of Symmetry, the Acute Bisectrix: Crossed Dispersion.*— With a section perpendicular to the acute bisectrix the centre of the figure is an axis of symmetry. The optic axes may lie in different planes, all passing through this axis. Fig. 357 shows a possible disposition of the axes: the axes for red occupy a different position from those for blue (dotted); each pair is symmetrical about the common bisectrix S. Hence the interference-figure in white light will have no line of symmetry but is symmetrical about its centre. This is well illustrated by borax, whose interference-figure displays colours which are always the same at equal distances on opposite sides of the bisectrix but have no other symmetry.

(2) *Axis of Symmetry, the Obtuse Bisectrix: Horizontal Dispersion.*— Here the optic axial planes are, as before, a series of planes intersecting in the axis *b*, but in a section perpendicular to the acute bisectrix they

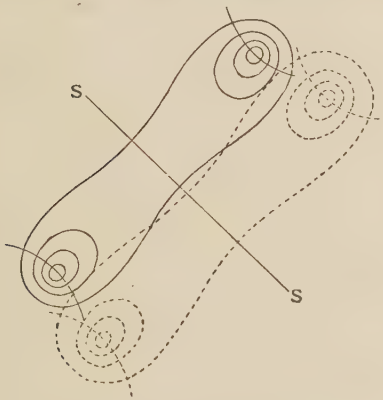


Fig. 358.—Horizontal Dispersion.

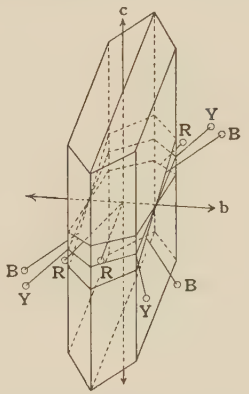


Fig. 359.—Crossed and Horizontal Dispersions.

are now viewed along a line in the plane of symmetry S, not along the axis *b*; consequently the optic axes for different colours must be situated, as in Fig. 358, so as to be all symmetrical to the plane S. The interference-figure in white light has one line of symmetry S, perpendicular to the line joining the optic axes. This is illustrated by some varieties of adularia felspar, in which the disposition of the interference-colours is symmetrical about the line perpendicular to the axial plane. Fig. 359 illustrates both these dispersions, and indicates that a crystal which shows crossed dispersion about its obtuse bisectrix must show horizontal dispersion about the acute bisectrix, and *vice versa*.

(3) *Axis of Symmetry, the Third Mean Line: Inclined Dispersion.*— Here the optic axial plane is the plane of symmetry. In a section perpendicular to the acute bisectrix the optic axes may lie as in Fig. 360; both the optic axes and the bisectrix may be dispersed in either direction in the plane of symmetry. Hence the figure as seen in white light has only one line of symmetry, S, joining the optic axes (see Fig. 360). In this case the dispersion is often recognisable, not only by the symmetry of

the colours, but also by the difference of size of the rings about the two optic axes (Fig. 360).

In the above dispersions a line of symmetry in the interference-figure shows the direction of the corresponding plane of symmetry in the crystal, and a centre of symmetry that of an axis.

As in the orthorhombic system, there are also in the monoclinic system crystals in which the axial plane for one colour is at right angles to that for another; thus the obtuse bisectrix for blue and the third mean line for red may coincide with *b*, when the optic axes for red will lie in the plane of symmetry, and those for blue in a plane perpendicular to the same, while for some intermediate colour the crystal will be uniaxial. the optic axis lying in the plane of symmetry.

The effect of the dispersion of the indicatrix-axes in a monoclinic crystal may often be detected when a section parallel to the face (010) is examined in *parallel* light; for if the extinction-lines are not coincident for all colours the section will never become quite dark but will change from a bluish to a yellowish shade as it passes through the extinction-position.

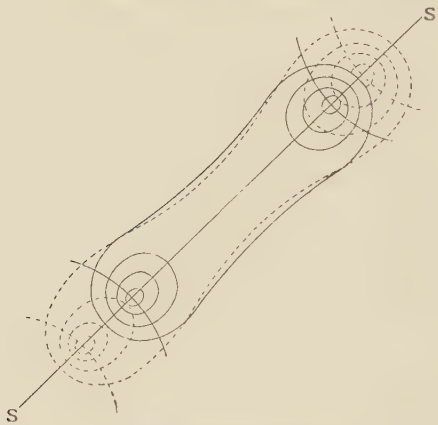


Fig. 360.—Inclined Dispersion.

Anorthic System.—The dispersions of the optic axes and of the bisectrices may here be in any directions; consequently the interference-figure seen in white light does not necessarily possess any symmetry.

26. **An Optical Classification of Crystals.**—It will be seen that the form and orientation of the indicatrix may be adopted as a basis of classification of crystals, and that the result harmonises with the grouping into six systems already adopted (p. 41).

(1) The indicatrix for any one colour is spherical (differing in radius for different colours).—*Cubic System.*

(2) The indicatrix for any one colour is a spheroid whose axis of rotation is parallel to the principal axis of the crystal (its axes differ in length for different colours).—*Tetragonal and Hexagonal Systems.*

(3) The indicatrix for any one colour is an ellipsoid with three unequal axes (which differ in length for different colours):

(*a*) The ellipsoids for different colours have all three axes parallel.—*Orthorhombic System.*

(*b*) The ellipsoids for different colours have *one* axis in common and fixed in direction.—*Monoclinic System.*

(*c*) The ellipsoids for different colours have no axis in common.—*Anorthic System.*

27. **The Absorption of Light—Pleochroism.**—We have seen above that

a section of coloured tourmaline cut parallel to the principal axis transmits only light which we may regard as vibrating along the axis; the other ray is completely absorbed. It is evident, then, that the absorption of light depends upon the direction in which the light vibrates within the crystal.

Although few minerals possess so marked a difference of absorption as tourmaline, in which one ray is completely absorbed when the crystal is sufficiently thick and deeply coloured, many possess the property in a less degree, so that light of a given colour is more absorbed when vibrating in one plane than when vibrating in another. Now the plane of vibration of transmitted light varies with the direction of transmission; hence in such crystals, if white light be employed, the colour of the crystal will appear different, according to the direction in which the light is transmitted.

This property, which is called "dichroism," or more generally "pleochroism," is especially marked in the case of cordierite, a mineral which is also known by the name of dichroite in allusion to this change of colour. A crystal of cordierite held up to the light and viewed in one direction appears bluish; in another direction it appears yellowish. The character is one of considerable importance in distinguishing between several of the precious stones. Sapphire, ruby, chrysoberyl, and kunzite are distinctly pleochroic. The property is also one of importance in the recognition of minerals in the microscopic sections of rocks.

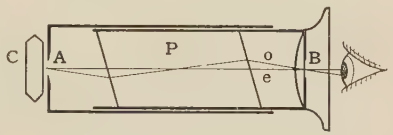


Fig. 361.—The Dichroscope.

There are two ways of examining the pleochroism.

The two plane-polarised beams which can traverse the crystal in a given direction are differently absorbed: in one beam, light of one colour is the most absorbed; in the other beam, light of some other colour is the most absorbed. When they emerge from the crystal they will be differently coloured, and the two beams may either be observed successively or simultaneously; they are observed successively under the microscope (see p. 198); they are observed simultaneously by means of the dichroscope.

The dichroscope consists simply of a long cleavage-rhomb of calcite P (Fig. 361) mounted in a tube which has a small square aperture A at one end, and at the other a lens B, by which the aperture is viewed through the calcite and magnified. Owing to its strong double refraction the calcite produces two images of the aperture, and the length of the rhomb is chosen so that the two images are seen side by side without overlapping. Owing to the obliquity of the end-faces of the rhomb, the extraordinary image occupies nearly the centre of the field of view, while the ordinary image is deflected.[1] The former is due to vibrations along the shorter diagonal of the rhomb (the line joining the two images), the latter to vibrations along the longer diagonal.

[1] In some instruments the ends of the rhomb are cut off at right angles to its longer edges. In this case the ordinary image is central, while the extraordinary is deflected; the dichroscope should therefore be tested before use.

In using the dichroscope it is only necessary to direct the instrument towards a window or other source of white light, to hold the crystal or section (C) in front of the small square aperture and turn it round until the two images are as differently coloured as possible.

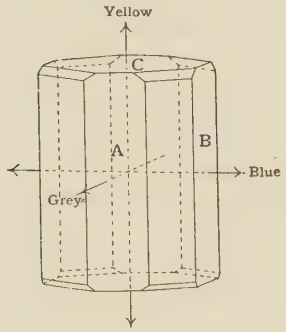


Fig. 362.—Cordierite.

A crystal of the orthorhombic cordierite (Fig. 362) examined in different directions by the dichroscope shows the following colours.

When the light is due to vibrations taking place parallel to the macro-diagonal it is deep blue; when vibrating parallel to the brachy-diagonal it is greyish-blue; while that vibrating parallel to the vertical axis is yellow. Hence viewed through the basal plane the colours of the two dichroscope images are grey and blue (Fig. 363); viewed through the brachy-pinakoid the two colours are grey and yellow; viewed through the macro-pinakoid they are blue and yellow. Each face is *dichroic*; the crystal as a whole is *pleochroic*. These colours are called the "axial colours."

Viewed by ordinary light without the dichroscope, the colour transmitted by the basal plane will be a blue, which is a mixture of the two axial colours belonging to the macro- and brachy-diagonals; similarly the colour of the brachy-pinakoid will be a yellowish-green; that of the macro-pinakoid bluish-green.

Fig. 363.—The Axial Colours of Cordierite viewed through C.

These mixed colours, due to the combination of the axial colours and seen when the crystal is viewed by ordinary light, are called the "face-colours."

28. **Rotatory Polarisation.**—A remarkable property possessed by crystals of quartz is the power of rotating the plane of polarisation of light transmitted in the direction of the principal axis. As is well known, this rotatory property is also possessed by the solutions of certain organic substances, such as sugar and tartaric acid, which crystallise in enantiomorphous forms and possess an unsymmetrical chemical constitution; but the property was discovered first in quartz.

Rays of plane-polarised light travelling through a plate of quartz in the direction of the optic axis emerge as plane-polarised light, but the plane of polarisation on emergence is not parallel to that of the incident light, having been rotated about the optic axis through an angle which depends upon the thickness of the plate and upon the colour of the light.

The angle of rotation is proportional to the thickness of the crystal and is nearly proportional inversely to the square of the wave-length of the light.

The angle of rotation in quartz for each millimetre of thickness is approximately:

For red light	(Line C)	19°
„ yellow light	(„ D)	22°
„ blue light	(„ F)	33°
„ violet light	(„ G)	43°

In the annexed diagram (Fig. 364), if PP be the direction of vibration in the polariser, the directions of vibration of red, yellow, blue and violet light, after passing through a basal section, six millimetres in thickness, of quartz which rotates the plane to the right (*i.e.* in the direction of a clock-hand) as seen by the observer, will be represented by the lines R, Y, B, and V respectively. Consequently, if daylight be used, and AA be the vibration-direction in the analyser, the only light completely extinguished will be a greenish-blue, whose direction of vibration is perpendicular to AA. The light of other colours will be resolved into two components, parallel and perpendicular to AA, of which the former only will be transmitted, so that most of the red and violet light and a smaller proportion of the other colours will reach the eye, and the section will appear orange. If the analyser be placed with its direction of vibration along PP, the extreme red and violet will be extinguished, and the section will appear green. If it then be turned to the right (or in the direction of a clock-hand), the colours will be extinguished in the order red, orange, yellow, green, and the green colour will change to blue, purple and red as the analyser is rotated.

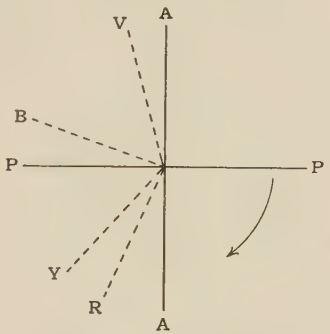


Fig. 364.—Rotatory Polarisation by Right-handed Quartz.

Some crystals of quartz rotate the plane of polarisation to the right; others rotate it to the left.

Thus in a dextro-rotatory or right-handed quartz crystal, a right-handed rotation of the analyser will cause the section to assume a succession of vivid tints which pass from blue, through purple, to red.

In a left-handed quartz crystal the same succession of tints is produced by a left-handed rotation of the analyser; in this way it is easy to distinguish between the two sorts of crystals.

Examined between crossed nicols in convergent light the section will give the ordinary uniaxial interference-figure, with the exception that the centre of the field corresponding to the light which has traversed the crystal along the principal axis is occupied not by the centre of a black cross but by a patch of colour (Fig. 365), the tint depending upon the thickness of the section; and this central patch of course changes tint, as just explained, when the analyser is rotated.

It was shown by Brewster and Herschel that the rotatory polarisation is intimately related to the crystalline form. A quartz crystal which is optically right-handed is also right-handed in the crystallographic sense used on p. 79. Of the two enantiomorphous crystals of quartz shown

in Figs. 198, 199, one (Fig. 198) is optically right-handed, the other (Fig. 199) is optically left-handed.

The only other mineral known to show rotatory polarisation is cinnabar, which possesses a rotatory power more than thirteen times as great as that of quartz. Cinnabar also belongs to the quartz class of crystals.

Several other uniaxial substances, however, possess the same power, not only hexagonal substances, as calcium dithionate, strontium dithionate and sodium periodate, but also tetragonal, as strychnine sulphate.

In addition to these, certain crystals belonging to the cubic system, such as sodium chlorate and sodium bromate, also rotate the plane of polarisation; in the uniaxial crystals the rotatory polarisation can only be observed in the direction of the optic axis, but in those of the cubic system plane-polarised light is rotated through an angle depending only upon the thickness of crystal traversed, whatever the direction of the light. In this respect, therefore, an optically active cubic crystal behaves exactly like an optically active solution. Most of these substances resemble quartz in crystallising in enantiomorphous forms, and of the two supplementary crystals one is always right-handed and the other left-handed in the optical as well as the crystallographic sense.

Fig. 365.—Interference-figure of Quartz.

It has frequently been supposed that all enantiomorphous crystals belonging to the cubic or uniaxial systems are optically active, and conversely that all optically active crystals must be enantiomorphous. This, however, has not been proved, for cuprite, sal-ammoniac and barium nitrate do not appear to rotate the plane of polarisation, and there is no evidence that calcium and strontium dithionates are enantiomorphous.

Certain biaxial crystals have also been found to exhibit optical activity in the direction of their optic axes; but owing to the peculiar properties of the optic axes in biaxial crystals the effects are difficult to observe.

29. **The Optical Constants.**—In order to define accurately for any mineral all the "crystallo-optical" characters which have been described above, and to express them in numbers, it is necessary to know the lengths of the axes of the indicatrix for different colours, and their orientation in the crystal. When the lengths and the directions of the axes of this ellipsoid have been determined for light of any one colour, then the refractive indices, the double refraction and the extinction-directions of any section, and the optic axial angle, for that colour, can be accurately deduced. When, further, the relative orientation of the ellipsoids for different coloured lights have been determined, the dispersions of the optic axes and of the bisectrices are also known.

Now in a biaxial crystal the lengths of the axes of the indicatrix for a certain colour are simply $OA=\alpha$, $OC=\gamma$ (the minimum and maximum

refractive indices for that colour) and OB = β, the refractive index which is common to rays transmitted in different directions in the plane AOC, Fig. 319.

The main constants to be determined are therefore the three indices of refraction for light polarised in the planes BOC, COA, AOB; or, to use the language employed above, for light vibrating along OA, OB, OC.

These three indices of refraction are called the three "principal indices" of the crystal. The same three letters, $\alpha\ \beta\ \gamma$, are often also used to denote the axes to which these indices severally correspond.

In the monoclinic system the directions of the indicatrix-axes may be defined by stating the position of the optic axial plane (*i.e.* the plane $\alpha\ \gamma$), parallel or perpendicular to the plane of symmetry (010), and the angle between one of the indicatrix-axes and the vertical crystal-axis *c*. If this indicatrix-axis is situated in the obtuse angle of the crystal-axes *ac*, its inclination to *c* is sometimes called positive; if in the acute angle it is called negative. To avoid confusion, however, it is better to *state* in which angle the indicatrix-axis lies, or to give its inclination to *two* face-normals as is done in the descriptions in Part II of this book (*e.g.* under diopside, p. 473).

The absorption of light in a crystal is usually described by reference to the same three lines; for this purpose it is only necessary to state the colour of the transmitted light vibrating along each of the three axes, and the relative magnitude of the absorption. Thus the absorption of cordierite is completely defined as follows: "$\alpha = c$, $\beta = a$, $\gamma = b$" (which gives the position of the axes); "α yellow, β grey, γ blue" (which gives the axial colours); "absorption for γ > absorption for β > absorption for α" (which gives the relative magnitudes of the absorption for vibrations along the axes γ, β and α respectively).[1] It will be remembered that the relative magnitudes of the refractive indices themselves are *always* $\gamma > \beta > \alpha$.

Similarly, for a uniaxial crystal, such as tourmaline, reference is made to the vibration-directions corresponding to the ordinary and the extraordinary indices ω and ϵ (*e.g.* for tourmaline, "absorption for ω > absorption for ϵ").

There does not seem any reason why in biaxial crystals (except in the orthorhombic system) the principal axes of absorption should coincide with the axes of the indicatrix, which are merely characteristic of refraction; indeed, in the case of epidote it has been proved that they do not coincide; but the former are difficult to discover, so that the character of the absorption is generally expressed by reference to the axes of the indicatrix.

The following two examples, beryl as a uniaxial, and diopside as a biaxial mineral, show how the optical constants may be conveniently described.

[1] Many authors use the symbols $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, to denote the absorption corresponding to α, β, γ respectively; with this notation the above character of cordierite would be expressed:— $\mathfrak{c}\ (b) > \mathfrak{b}\ (a) > \mathfrak{a}\ (c)$. Others, however, use these letters, $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, to denote the lengths of the axes of the Fresnel ellipsoid, *i.e.* $\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}$.

Beryl (Fig. 175).—Birefringence ($\epsilon - \omega$) negative, weak.

	Red (Li).	Yellow (Na).	Green (Tl).
ω	1·586	1·589	1·592
ϵ	1·579	1·582	1·584
$(\epsilon - \omega)$	−·007	−·007	−·008

Pleochroism weak : ϵ bluish, ω green.

Refractive power (mean of the refractive indices for sodium light) weak = 1·585.

These numbers indicate that beryl does not possess the brilliancy belonging to minerals whose refractive power is strong; that its pleochroism (difference of axis-colours) is not marked; and that a thin section viewed between crossed nicols will give colours of low orders as compared with minerals of strong birefringence.

Diopside (Fig. 366).—Birefringence positive, strong; axial plane (010).

	Red (Li).	Yellow (Na).	Green (Tl).
α	1·6675	1·6710	1·6749
β	1·6744	1·6780	1·6818
γ	1·6962	1·7000	1·7045
$(\gamma - \alpha)$	0·0287	0·0290	0·0296
$c\,\gamma$	+39° 12′	+39° 6′	+39° 3′
2V	58° 52′	58° 43′	58° 30′

Pleochroism weak : α olive-green, β grass-green, γ grass-green.

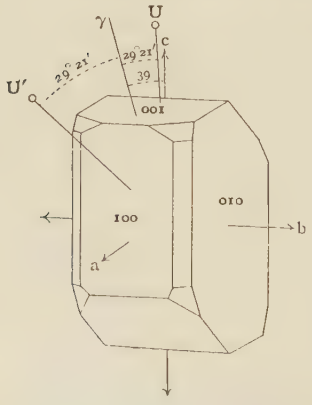


Fig. 366.—Optic Axes of Diopside.

The above numbers show that the refractive power β and the birefringence $(\gamma - \alpha)$ are strong. The acute bisectrix is inclined at about 39° to the vertical axis in the obtuse angle between a and c, and is the vibration-direction corresponding to the index γ. The dispersion of the bisectrix is very slight, not more than 9′ for red and green light; the dispersion of the optic axes is $\rho > v$, but it is very slight, being only 22′ for red and green light.

The mineral possesses marked brilliancy and very slight pleochroism, and thin sections give interference-tints of high orders as compared with beryl.

The positions of the optic axes U,U′ and of the acute bisectrix γ are given in Fig. 366.

CHAPTER VII

THE DETERMINATION OF THE OPTICAL PROPERTIES BY THE MICROSCOPE AND GONIOMETER

It now remains to show how the optical constants of a mineral are practically determined or estimated. Measurement of the three principal indices of refraction of a biaxial crystal by the ordinary prism-method would require two prisms cut symmetrically out of the crystal, each with its edge parallel to one of the axes of the indicatrix and having its angle bisected by one of the planes of symmetry of the latter. Each prism would then yield two refracted images of the collimator slit when examined by means of the goniometer of Fig. 275, and each image would suffice for the measurement of one index by the method of minimum deviation as described in all text-books of physics.

For the practical purposes of the mineralogist in the identification of a transparent mineral it is generally sufficient to measure the mean refractive power and the birefringence, and to find the position of the optic axes, and the sign of the birefringence. The dispersion of the optic axes or of the bisectrix can be sufficiently estimated by observation of the interference-figure in white light.

1. **The Refractive Power and the Birefringence.**—The refractive power of a crystal may often be determined by employing two natural faces as a refracting prism, and using the goniometer to measure (1) α, the angle of the prism as defined on p. 33 ; (2) δ, the angle of minimum deviation of the light traversing the prism. The index of refraction μ is then given by the formula

$$\mu = \frac{\sin \frac{(180^\circ - \alpha) + \delta}{2}}{\sin \frac{180^\circ - \alpha}{2}}.$$

The crystal will in general yield two images of the collimator slit, which may be seen side by side in the field of the telescope, and from them two indices of refraction will be obtained ; their mean may be taken to represent the refraction, and their difference the birefringence of the crystal *in the direction of the transmitted light* (*m n* in Fig. 367).

If the mineral be uniaxial and the faces be two faces belonging to

prism-forms, these two indices will be actually ω and ϵ, and their difference will be the accurate measure of the birefringence of the mineral. For of the two rays refracted through such a prism, one vibrates along a horizontal and the other along the vertical line, since the rays themselves travel in the horizontal plane. Fig. 367 represents the refraction of light through the faces $m\,n$ of a hexagonal prism belonging to a positive substance.

Any prism whose refracting angle is bisected by a principal plane of the crystal will give ω and ϵ, since in the position of minimum deviation the direction of the wave in the crystal will be perpendicular to the optic axis.

A prism whose bisecting plane is perpendicular to the principal axis of the crystal will give, in the position of minimum deviation, a single

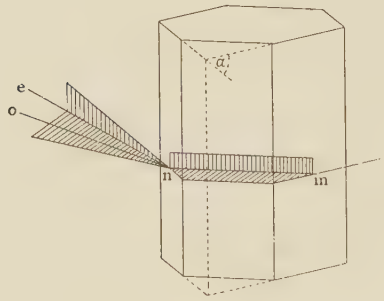


Fig. 367.—Refraction through Prism of Uniaxial Crystal.

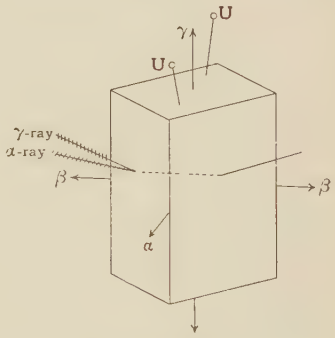


Fig. 368.—Refraction through Prism of Biaxial Crystal.

image only, corresponding to the index ω, since the light will then be travelling along the optic axis.

A prism cut in any other direction will give two indices, one of which is ω, while the other lies between ω and ϵ.

Among biaxial minerals only those belonging to the orthorhombic system are likely to yield natural prisms suitable for measuring both the refraction and the birefringence.

For example a prism of the positive orthorhombic mineral of Fig. 368 will, by virtue of its symmetry, transmit light which in the position of minimum deviation is travelling along the axis β, and therefore vibrating along the axes α and γ of the indicatrix; such a prism will therefore give the indices α and γ and the birefringence $(\gamma - \alpha)$. Unsymmetrical prism-faces, *e.g.* (110) and $(1\bar{1}0)$, on crystals of the same mineral will give γ and an index between α and β; but their difference will be less than $(\gamma - \alpha)$, so that such faces will suffice to determine approximately the refractive power but not the exact birefringence of the mineral.

This is also the case in general with prisms formed by natural faces of monoclinic or anorthic minerals. With such crystals, if observations be made with several pairs of faces, those which give the widest difference

between the two indices give, of course, a birefringence most nearly approaching the true birefringence ($\gamma - \alpha$) of the mineral.

Both the refractive power and birefringence of facetted gem-stones may very conveniently be measured approximately in this way by utilising a suitable pair of facets as a refracting prism.

For most minerals a prism of about 120° is convenient.

It should be remembered that any prism whose edge is parallel to one of the indicatrix-axes, such as OC, will give, as one of the two values, the corresponding index (γ), as shown in Fig. 368. Thus one principal index of a monoclinic crystal will always be given by a prism whose edge is perpendicular to (010).

Total Reflection.—If the refractive indices of a mineral be below 1·74 they may be very conveniently measured by the method of total reflection. When light travelling in a medium whose refractive index is n meets the surface where the medium is in contact with a crystal whose refractive index μ is less than n, then, if the angle of incidence be equal to or greater than the critical value R, where $\sin R = \frac{\mu}{n}$, the light is totally reflected. If, then, the index n of the medium be known and the angle R of total reflection can be measured, the index μ may be ascertained.

The measurement can be thus made by the telescope-goniometer of Fig. 275.

A prism ABD of highly refracting glass is mounted on the crystal-holder and adjusted with its three faces parallel to the axis (Fig. 369). The crystal C is fixed to an adjustable holder so that one of its faces is in true contact with the face BD of the prism, and contact is assured by placing a drop of methylene iodide between C and BD. Diffused light enters the prism through AB, is reflected at the surface of C, and is observed through the telescope T. If the light from the direction of O_1 meets the surface of the crystal just at the critical angle, as at o, any ray meeting the surface more obliquely, such as P_1p, will be totally reflected, while less oblique rays, such as Q_1q, will be only partially reflected, a portion of the light passing into the crystal and being lost. The rays will be brought to a focus in the telescope at O_2, P_2, Q_2, respectively, and one part (P_2) of the field of the telescope will be more brightly illuminated than the other (Q_2), the edge of the "shadow" corresponding to the rays O_2 which have been reflected at the critical angle. The angle of emergence through AD of the rays corresponding to the edge of the shadow is measured; and, the angle of the glass prism and its refractive index being known, the angle of total reflection (R) can be easily found. The refractive index of the crystal can then be calculated from the known index of the prism.

The same critical angle, at which total reflection begins when light is incident upon the dividing surface *from* the medium with the higher index, may also be found by allowing light to reach the surface from the *opposite* side at an incidence near 90°. Light thus entering the more refractive medium at "grazing incidence" is refracted towards the normal, and the limiting angle of refraction (for an incidence of 90°) is the same as the angle of total reflection. The incident light here travels in the

less refractive medium parallel to the surface, along the line in which this intersects the plane of incidence, and if the medium is a doubly refracting crystal the refractive index found will be that corresponding to light travelling through it in this direction. If this is not an optic axis there will be two refractive indices, μ_1 and μ_2, corresponding to the two rect-

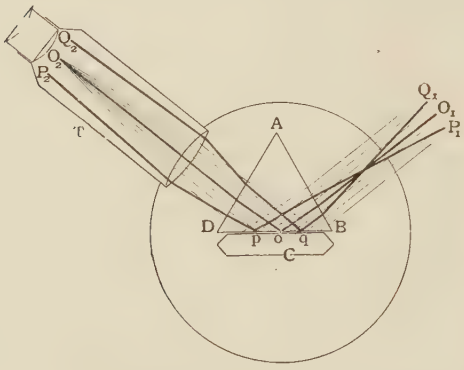


Fig. 369.

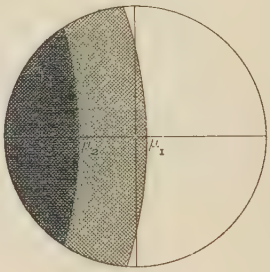


Fig. 370.

Measurement of Refractive Indices by Total Reflection.

angular vibrations; and the two shadows may be distinguished by means of a nicol prism.

The same two refractive indices will be obtained if the light is incident on the surface through the glass prism, as before described. The field will then appear as in Fig. 370.

If the crystal plate be turned round in its own plane, while remaining in contact with the prism, every line lying in this plane will come successively into the plane of incidence, and the shadows will change their position in accordance with the refractive indices of the crystal for light travelling in these directions. In a plate cut (in any direction) from a biaxial crystal the highest and lowest indices obtained will be γ and α respectively, and their difference will measure the birefringence.

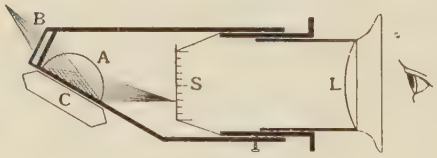


Fig. 371.—Total Reflectometer.

The small total reflectometer shown in Fig. 371 is a convenient instrument by which an approximate measurement of the refractive power and birefringence of a crystal or gem-stone may be quickly and easily made.

At one end of the tube represented in Fig. 371 is a hemispherical lens A of highly refractive glass, with its centre in the axis of the tube and the plane surface inclined at about 30° to the axis. Diffused light falls upon this through a ground glass at B. S is a scale engraved upon glass, and L is a lens through which S is viewed. A plane face of the crystal C being pressed against the front of A after a drop of methylene iodide

has been interposed between C and A, the light whose incidence on C is sufficiently oblique suffers total reflection. A corresponding portion of the scale is more brilliantly illuminated than the remainder, and, as before, two shadows, D, E (Fig. 372), are seen across the field of view; these correspond to two refractive indices of the crystal, and by rotating the crystal as above described the principal indices γ and α may be found. It is necessary to calibrate the scale beforehand by placing different isotropic substances, liquid or solid, of known refractive index against A; these should be viewed by sodium light and the corresponding points of the scale which are intersected by the shadow are to be noted for each. The refractive indices corresponding to a number of readings on the scale are thus ascertained, and the value of the remainder can be found by constructing a curve.

The interval between the shadows D, E, indicates at a glance the magnitude of the birefringence.

The film of liquid, having its surfaces parallel, does not alter the angle registered by either instrument; and its refractive index need not be known. Its use is to eliminate the film of air, which by total reflection would prevent the light from reaching the crystal.

Other liquids of higher refractive index might be employed, but they are for the most part corrosive or unstable. One of the most convenient of all liquids is α-monobromnaphthalene, whose index is 1·66, and therefore considerably less than that of methylene iodide ($n = 1{\cdot}74$), but it does not darken on exposure to light so readily as the latter.

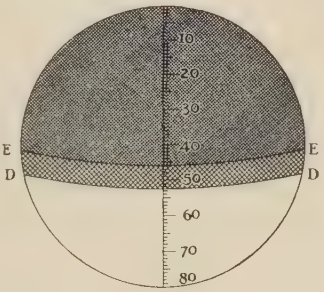


Fig. 372.—Field of Reflectometer.

The refractive index is frequently of use in the determination of minerals, and simple methods by which it can be approximately estimated will be described later (Book V, Ch. II, pp. 323, 325).

2. **The Sign of the Birefringence.**—The sign of the birefringence of a mineral fragment, section, or crystal is ascertained by superposing upon it, under the microscope, a slice of some crystal whose birefringence is known, and observing in what positions the latter increases or diminishes the effect of the crystal.

This can be done most conveniently in convergent light by observing the change in form of the interference-figure.

The test-crystals used are: (1) for uniaxial crystals a "quarter wave-length mica plate"; and (2) for biaxial crystals a "quartz wedge."

3. **Use of the Mica Plate with Uniaxial Crystals.**—Mica is a biaxial mineral (monoclinic) which very readily cleaves nearly perpendicular to the acute bisectrix; the cleavage-flakes may be obtained of any thinness required. A cleavage-plate by which the two sets of waves, of light of mean colour, travelling through it (along the acute bisectrix) are made to differ in phase by a quarter of a wave-length is called a "quarter wave-length plate."

Viewed in convergent light such a plate will itself give an interference-figure, in which the first ring is continuous and shaped like the second ring of Fig. 373.

The plate is cut into an oblong form (Fig. 374), with its greatest length parallel to the plane containing the optic axes, and mounted

Fig. 373.—Relative Retardation less than 1 Wave-length.

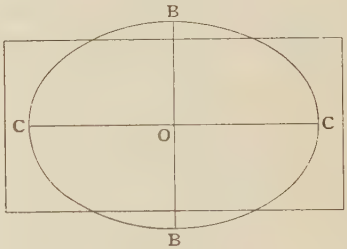


Fig. 374.—Birefringence of Mica Plate.

for protection between two slips of glass. Mica is optically negative, so that of the two extinction-lines in the plate, one, OB, is the mean axis of the indicatrix, proportional to the index β of the mica, and the other, OC (the obtuse bisectrix), is the greatest axis, proportional to the index γ. Fig. 374 shows the nature of the elliptic section of the indicatrix by the mica plate. A ray entering the plate is divided into two, one vibrating along OB and travelling faster, the other vibrating along OC and travelling more slowly; and in their passage through the plate the latter is retarded $\frac{1}{4}\lambda$ more than the former.

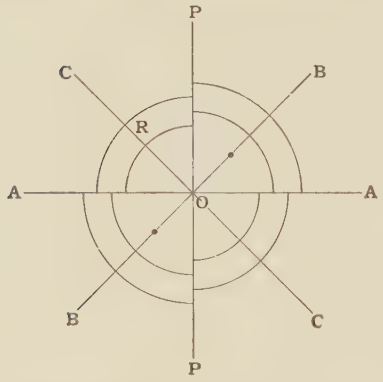


Fig. 375.—Action of Mica Plate on a Positive Uniaxial Figure.

Consider the effect upon a uniaxial figure of such a plate inserted in the microscope tube between the objective and the analyser. Fig. 375 represents the interference-figure of a positive uniaxial mineral with the mica plate inserted above it along the line CC, at 45° to the lines PP and AA.

Any point R of the first ring, where the relative retardation is λ, corresponds to two rays, one, the extraordinary, vibrating along RO, which is parallel to OC; the other, the ordinary, vibrating parallel to OB (*cf.* Fig. 343). Since the crystal is positive the latter is the minor axis of the indicatrix belonging to the crystal, and therefore the ray vibrating

in that direction corresponds to a lesser refractive index and travels more rapidly than the other in the crystal section. This ray also travels more rapidly in the mica plate; the relative retardation will therefore be $\lambda + \frac{1}{4}\lambda$ instead of λ, and there will be light instead of darkness at the point R. The first dark ring will be produced in the position shown, between R and O, where the relative retardation due to the crystal alone was $\frac{3}{4}\lambda$, which is increased by the action of the mica plate to λ, so that complete interference takes place after analysation.

The effect of the mica plate will be added to the effect of the crystal in the two quadrants bisected by CC, and in these quadrants the rings will all be shifted inwards towards the centre by one quarter of the distance between two rings. The result is the same as though the crystal section were increased in thickness, the rings being drawn closer together.

In the remaining two quadrants the effect is just the contrary. Here again the extraordinary ray vibrates in the plane containing the ray and

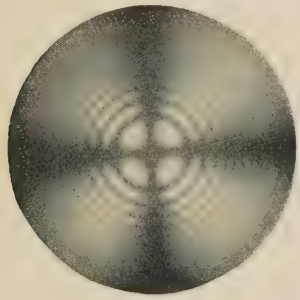


Fig. 376.—Uniaxial Figure.

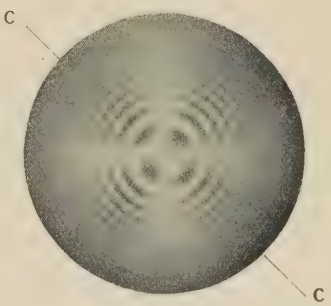


Fig. 377.—Uniaxial Figure with Mica Plate inserted along CC (Positive Crystal).

the optic axis; but this plane is now parallel to the line OB in the mica plate, while the vibrations of the ordinary ray are parallel to OC; thus the minor axis of the indicatrix of the crystal is here parallel to the major axis, OC, of the mica. In these quadrants, therefore, the action of the mica plate is opposed to that of the crystal; the result is the same as though the section were made thinner, and the diameters of the rings are increased. At two points in these quadrants, where the relative retardation due to the crystal is $\frac{1}{4}\lambda$, the double refraction of the crystal is exactly annulled by that of the mica, and at each of these points there will be a dark spot, while the centre of the field becomes light, owing to the uncompensated effect of the mica.

With a positive crystal, then, the rings expand along the breadth of the mica plate and contract along its length. In a negative crystal the vibration-directions corresponding to greatest and least velocity are interchanged, and the same considerations will show that the rings must expand along the length of the mica plate and contract along its breadth.

The effect of the mica plate on the uniaxial interference-figure of Fig. 376 is shown in Fig. 377.

As a *memoria technica* it may be noted that the line along which the optic axis opens out into two dark spots forms a *plus* sign with the length of the mica plate in a positive crystal, and a *minus* sign in a negative one.

The mica plate cannot be conveniently used with extremely thin sections in which the rings are very widely separated. In such cases a "sensitive plate" of gypsum may be used, as indicated in Article 6, below.

4. **Use of the Quartz Wedge with Biaxial Crystals.**—The method of noticing in what positions a crystal of known sign apparently increases the thickness of a section, and in what positions it apparently diminishes it, when placed over the section, is also utilised in determining the sign of biaxial crystals. But here the mica plate cannot be so conveniently used, since there is no point like the centre of the uniaxial figure through which the vibration direction of one of the rays always passes.

Quartz is a positive mineral. A section cut from a long prism of quartz parallel to the optic axis is therefore one in which the length of the section is the vibration-line of rays corresponding to least velocity or greatest refractive index; in this respect it resembles the mica plate. A section cut thus parallel to the optic axis so as to be thinner at one end than the other (*i.e.* a wedge-shaped section) will, when examined between crossed nicols in parallel light, exhibit tints which vary with the thickness of the section. At the thinner end, if sufficiently thin, it may show the grey, white, and yellow of the first order of Newton's scale; and the colours will rise gradually through the second, third, and higher orders as the wedge is examined successively farther and farther from its thinnest part; bands of one colour after another will appear in succession as the wedge is moved across the stage. Such a wedge affords the means of superposing any desired thickness of quartz upon the section which is being examined.

The quartz wedge should be as thin as possible at its edge and increase very gradually towards its thicker end. In the examination of biaxial interference-figures it is (like the mica plate) inserted through an aperture in the tube between the objective and the analyser, so that its length, the line of the optic axis, is inclined at 45° to the planes of the polariser and analyser.

Let Fig. 378 represent the interference-figure seen along the acute bisectrix of a *negative* biaxial crystal in the diagonal position, and let the quartz wedge be first inserted perpendicular to the line joining the optic axes of the crystal, as shown by the dotted lines. In the crystal, OB is the mean axis, OC the greater axis of the indicatrix; in the indicatrix of the quartz wedge, on the other hand, the major axis is parallel to OB, and the minor axis to OC. Hence, at the centre of the figure the quartz wedge will be acting in opposition to the crystal, and will produce the same result as though the section were made thinner. The rings at the centre of the figure will broaden out, and as the wedge is pushed farther and farther across the field of view, so that the thickness of quartz continually increases, each pair of rings surrounding the axes will be seen to expand. The pair of rings 1 pass successively into the form of 2, 3, and 4; they meet in the centre as a figure of eight and pass outwards as a continuous

oval curve in a direction at right angles to the line of the axes, as shown by the arrows.

Let the quartz wedge be now inserted parallel to the plane of the axes, along the line CC. The directions corresponding to the greatest and least indices in the wedge are now reversed, and the effect of the latter will be added to that of the crystal section. The result will be the same as though the section were increased in thickness, and the coloured rings will move towards the optic axes.

On the other hand, in a *positive* biaxial crystal the obtuse bisectrix, *i.e.* the extinction-line in the plane of the optic axes, is the least axis of the indicatrix, and the rings will expand when the quartz wedge is inserted parallel to the optic axes.

Hence in a negative crystal the rings expand outwards when the quartz wedge is inserted perpendicular to the plane of the optic axes; in a positive crystal, when it is inserted parallel to that plane.

It is well always to examine the section by inserting the wedge first in one of these directions and then in the other, and observing whether the rings expand outwards in one position of the wedge, and *also* contract inwards in the other. Otherwise it is sometimes possible to be misled by an apparent expansion due to the overlapping of the rings in white light, though the quartz wedge is acting in concert with the crystal. This does not occur with monochromatic light.

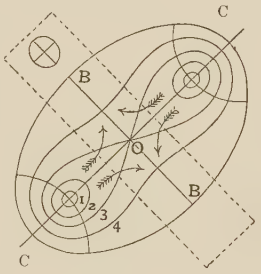


Fig. 378.—Action of Quartz Wedge on a Negative Biaxial Figure.

It must be noted that the above observations apply only to the central part of the field, between the convex portions of the brushes. The rings outside the axes, *i.e.* between the concave side of the brushes and the edge of the field, move in the opposite sense, for the corresponding rays lie between an optic axis and the *obtuse* bisectrix.

When the ordinary wedge is not thin enough,[1] it is convenient to use a quartz wedge on which is cemented a thin sheet of gypsum acting in opposition to the quartz and of just sufficient thickness to compensate it at its thin end. This end will then be dark and the colours of Newton's scale will follow in due order.

Another method is to use a quartz plate cut perpendicular to the axis. If such a plate be inserted in the microscope tube and slightly tilted by rotation about OB (Fig. 378), its optic axis (the major axis of its indicatrix) will lie in the plane OC; but the double refraction will be very slight, since the observer is looking very nearly along the optic axis, and the effect will be the same as that of inserting an extremely thin wedge along OC. A slight rotation of the plate about OC will be equivalent to inserting a very thin wedge along OB.

In a section perpendicular to the obtuse bisectrix the optic axes wil

[1] A quartz wedge seldom shows the dark grey of the first order, since its extreme end is apt to be broken away in the process of grinding.

lie outside the field and often no rings even are visible, the field being occupied by white of higher order; but by inserting a quartz wedge first in one direction and then in the other, it may be possible, by compensating, to bring the rings into view at two opposite sides of the field and thus to determine (1) the direction of the optic axial plane, and (2) the sign of the bisectrix.

5. **The Method of Compensation in Parallel Light.**—By the use of the wedge it is therefore possible, from the interference-figure in a section perpendicular to a bisectrix, to determine which of the two extinction-lines is the major axis of the ellipse in which the section cuts the indicatrix, *i.e.* is the vibration-direction of the slower ray; from this it is known whether the bisectrix (either the acute or obtuse bisectrix) is positive or negative. If the section be cut parallel to the plane of the optic axes of a biaxial crystal, or parallel to the optic axis of a uniaxial crystal, no interference-figure will usually be seen; but it will still be possible to determine which of the extinction-lines in the plane of the section is the greatest and which the least axis of the indicatrix. Or, more generally still, it is possible in *any* section cut from any birefringent crystal to determine which of the two extinction-lines is the vibration-line for the greater index. This is done by using the quartz wedge or some similar contrivance—not in convergent but in parallel light.

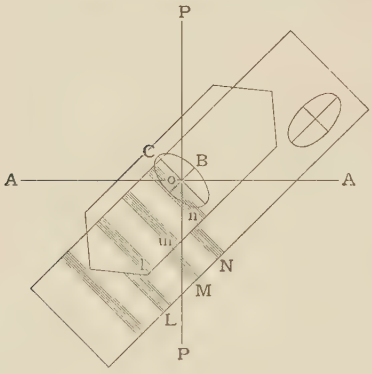


Fig. 379.—Compensation by Quartz Wedge.

Thus, let C in Fig. 379 represent any crystal section placed in the diagonal position, *i.e.* at 45° to its position of extinction, and of its two extinction-lines let OC be the greater radius, and OB the lesser radius of the ellipse in which it cuts the indicatrix, so that the section of the indicatrix is the ellipse shown in the centre of the figure.

If now the quartz wedge (whose corresponding ellipse is shown at its thicker end) be inserted along the line OB it will act in opposition to the section; the double refraction will be continually diminished—the tints of the section will fall in the Newton scale until finally a dull grey band will appear where the wedge exactly "compensates" the section, and the double refraction is neutralised. An increasing thickness of quartz will then cause the tints to reappear and to rise through the scale of colours. Whenever compensation can be effected, or the colours be made to descend in the scale, the wedge is known to be acting in opposition to the section.

The direction of compensation having thus been determined, the sign of the double refraction of the crystal may in some cases be ascertained, provided that the direction of the optic axis, or in a biaxial crystal that of the acute bisectrix and the axial plane, is known.

If, for example, a thin prism of a uniaxial mineral is compensated by the insertion of the quartz wedge parallel to its length, it must be negative, since it is acting in opposition to the quartz though their principal axes are parallel.

If the section is very thin or weakly birefringent, a plate of quartz cut perpendicular to its axis may be used as recommended above, the required double refraction being obtained by a very slight tilting of the quartz plate.

In some crystals, in which the birefringence for different colours varies differently from that in quartz, complete compensation cannot be obtained by means of a quartz wedge, since different colours will require a different thickness of quartz for compensation; but the *direction* in which the quartz wedge *tends* to compensate the crystal can usually be ascertained from the appearance of the colours produced.

With a thin or weakly birefringent crystal an easy way of determining whether the birefringence of the quartz wedge is increasing or diminishing the effect of the crystal is to observe the displacements of the bands of the wedge where the latter overlaps the crystal. Thus in Fig. 379 the wedge is so arranged as partly to overlap the crystal; a particular band as seen in the quartz alone is at M; but since the birefringence of the crystal is opposed to that of the quartz, the light, in order to produce the same effect, must traverse a greater thickness of quartz where it overlaps the crystal, the corresponding band therefore appears at *m*, and all the bands are displaced towards the thick end of the wedge (*l*, *m*, *n*, etc.).

If the quartz and the crystal are co-operating, the displacement is towards the thin end of the wedge.

6. **The Method of Sensitive Plates.** — As suggested by this last experiment, the change of tint produced, not in the crystal, but in the compensator itself, may be utilised to determine the sign of the birefringence. For this purpose the compensator is a thin section of some known mineral; for instance, a cleavage-lamina of gypsum cleaved so thin as to give the red of the first order as its interference-colour. When the crystal section adds its effect to that of the gypsum, the slightest change makes itself apparent in a rise of the colour to the blue or yellow of the second order; when the crystal section acts in opposition to the gypsum, the tint falls to the dark yellow or white of the first order.

Such a plate is extremely sensitive, and may be used in examining minerals whose double refraction is very weak; such, for example, as give only the grey of the first order. The positions of the extinction-lines in the gypsum and their relative magnitudes as radii of its indicatrix being known, a rise in the tint indicates that they are superposed on corresponding extinction-lines in the crystal; a fall in tint indicates that the vibration-direction corresponding to the larger refractive index in the gypsum coincides with that belonging to the less refractive index in the crystal.[1]

[1] When using a gypsum plate it is necessary first to ascertain, with the help of a quartz wedge, whether its length is parallel to the longer or shorter axis of the indicatrix-section, as the plates in use vary in this respect.

This method may also be used with convergent light. Thus, with a uniaxial crystal, the quadrants in which the crystal and plate are opposed will show a lowering of the sensitive tint (corresponding to the dark spots seen with a quarter wave-length plate), and *vice versa.*

7. **Determination of the Pleochroism.**—It was shown above (p. 182) how the dichroscope is used to place the two axial colours belonging to any crystal section side by side, so that they may be distinguished.

With the polarising microscope they may be viewed *successively* and determined with even minute fragments. For this purpose the analyser is removed and the polariser is used alone. Let Fig. 380 represent a pleochroic crystal (such as andalusite) lying on the microscope stage. Let BB and GG be its two extinction-lines, so that the vibrations of light traversing the crystal can take place along BB and GG. Let the former be brown in colour, and the latter green.

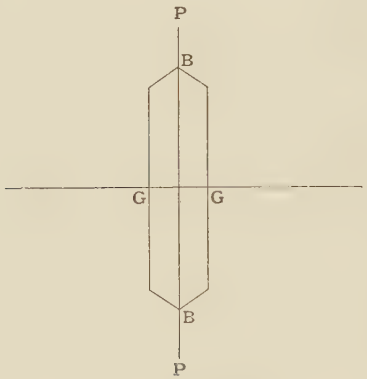


Fig. 380.—Pleochroism.

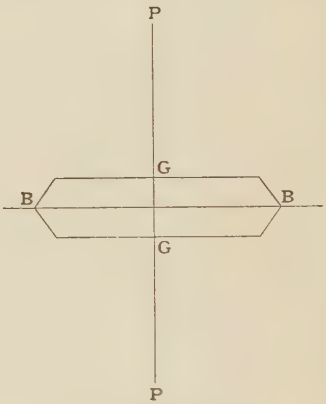


Fig. 381.—Pleochroism.

Then in the position of Fig. 380 the plane-polarised light from the polariser, whose vibration-direction is PP, traverses the crystal unaltered, as plane-polarised light vibrating along BB, and the section appears of a brown tinge.

Now let the stage be turned through 90°, so that the section lies as in Fig. 381. The rays transmitted by the polariser now traverse the crystal, vibrating along the direction GG, and the crystal appears of a green tint.

Hence a pleochroic crystal will change colour as the stage is rotated over the polariser; a crystal of coloured hornblende, tourmaline, or biotite (viewed along the cleavage) will show this property in a very conspicuous manner.

In tourmaline the ordinary ray is almost entirely absorbed; a thin prism of this mineral which appears fairly transparent and only faintly coloured in the position of Fig. 380, becomes dark brown and almost opaque when in the position of Fig. 381, in which its optic axis BB is parallel to the longer diagonal of the polarising nicol.

A crystal of mica viewed parallel to its cleavage, *i.e.* across and not along the hexagonal prism, appears dark when its cleavage-lines are parallel to PP (Fig. 382), since the light, whose vibration direction is in the plane of the cleavage, is more absorbed than the light vibrating perpendicular thereto.

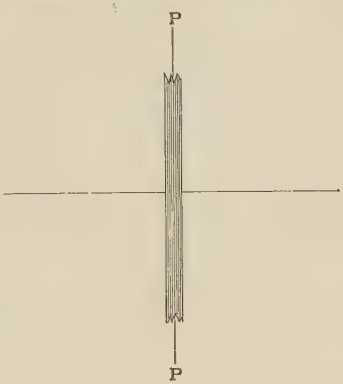


Fig. 382.—Mica in Position of Maximum Absorption.

8. **Measurement of the Optic Axial Angle.**—To measure 2E, the apparent optic axial angle in air of a biaxial crystal, a plate must be obtained which is perpendicular to the acute bisectrix, and the position of the optic axial plane must be ascertained by a preliminary observation of the plate in convergent light.

A good mineral for examination is topaz, which has a good cleavage parallel to the basal pinakoid, which is perpendicular to the acute bisectrix. The optic axes are seen to lie in the plane of the shorter diagonal of the cleavage-plate. The plate is then mounted on a "stage-goniometer," as shown diagrammatically in Fig. 383.

This is merely a small goniometer with the ordinary centreing and adjusting movements of Fig. 272, p. 113, which can be screwed to the stage of the microscope. The size of the crystal plate is much exaggerated in the figure.

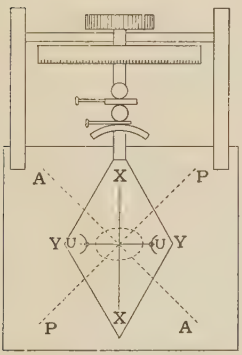


Fig. 383.—Stage-Goniometer.

It is advisable that the microscope should be of the "Dick"-pattern, in which the stage is fixed and the nicols rotate together (Fig. 384).

The crystal plate is to be carefully mounted and adjusted so that the axial plane UU is perpendicular to the goniometer axis (Fig. 383); the polariser and analyser are set so that their principal planes PP, AA are at 45° to the cross-wires of the eyepiece; the cross-wires XX, YY themselves being parallel and perpendicular to the goniometer axis.

By means of a screw shown below the stage (Fig. 384) the goniometer is raised so far that the plate can be turned round without coming in contact with the stage, and the microscope tube is racked up so far that the plate does not come into contact with the objective. This renders it impossible to see more than a small area of the interference-figure, quite near the centre of the field of view, but for purposes of measurement that is all that is required. For when the goniometer circle is turned in one direction the figure moves across the field of view until one optic axis approaches the centre of the field, and by turning the circle in the other direction the other optic axis can be brought into the centre of the field.

The plate is adjusted on the goniometer, so that as it is rotated, first one and then the other optic axis passes exactly along the horizontal cross-wire of the microscope. The adjustments are made just as in measuring a crystal on the goniometer.

Each optic axis is the central point of the apex of one of the hyperbolic brushes belonging to the biaxial figure; in order to ascertain when

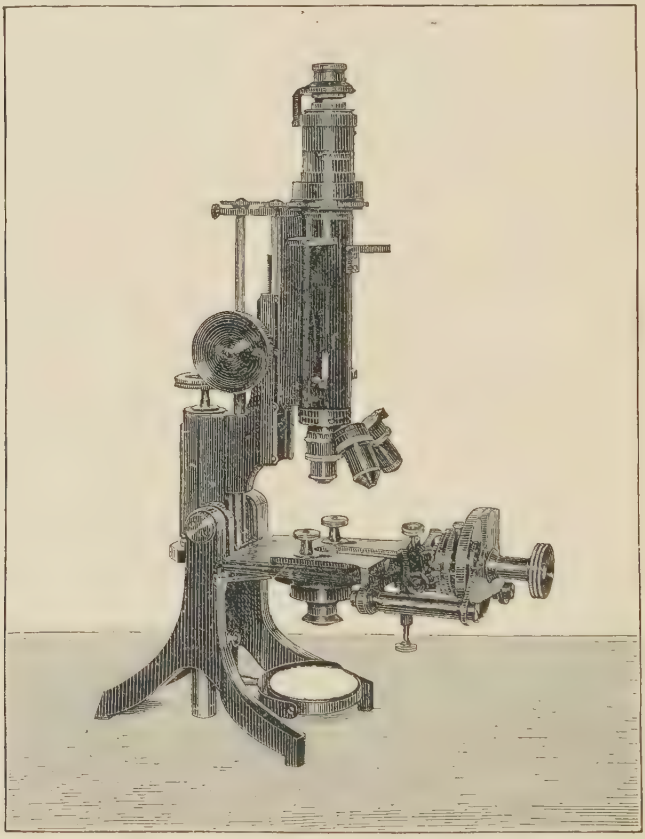


Fig. 384.—Microscope with Stage-Goniometer.

this point coincides with the centre of the field of view the goniometer circle is moved until first the convex side and then the concave side of the hyperbola is brought into contact with the vertical cross-wire. The two corresponding readings are noted and their arithmetic mean is taken as the reading for one optic axis; a similar reading is obtained for the other optic axis, and the difference between the two readings is the angle 2E. The disc is then turned until the plate is reversed; the measurement is repeated, and thus a second determination is made of the same angle.

From the apparent axial angle (2E) the true axial angle (2V) can be

deduced, if the mean index of refraction β is known, by means of the relation $\sin E = \beta . \sin V$ (see p. 174).

9. **Determination of 2V.**—It is also possible, by using a second plate, cut perpendicular to the obtuse bisectrix, to determine 2V without knowing the value of the indices of refraction.

It is not possible to measure the apparent obtuse angle in air ($2E_o$) by this plate, for $2V_o$ is so large that rays travelling in the crystal along the optic axes would experience total reflection at the surface of the plate.

When, however, the section is immersed in oil, or some other liquid, of which the refractive power is nearly equal to that of the crystal, total reflection no longer takes place ; it is generally easy to obtain a measurement even for the obtuse angle, and, further, by measuring both the acute

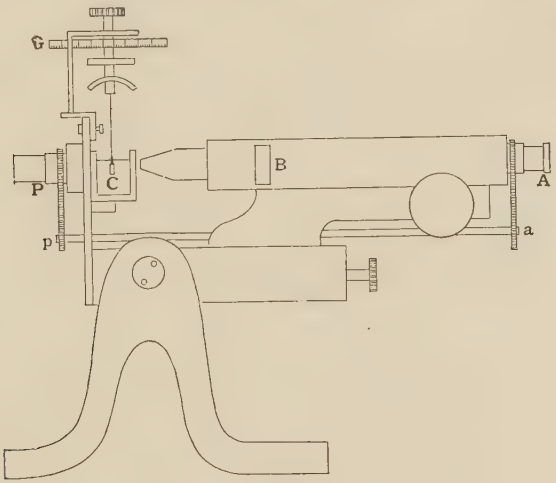


Fig. 385.—Measurement of 2H.

and the obtuse angle in the same oil, the true angle 2V can be found without even a knowledge of the refractive index of the oil.

For this purpose a small glass trough with parallel sides is filled with oil and inserted between the condenser and the objective, the microscope tube having been first placed in a horizontal position. The trough is inserted from below, so that the crystal section C is completely immersed in the oil, and the section is to be small enough to be rotated in the trough without coming into contact with the sides. No deviation of the ray is produced on its emergence from the oil into air, for the trough is enclosed by a pair of truly parallel plates, and is placed with its sides perpendicular to the axis of the microscope. In Fig. 385, the polariser and analyser, P and A, are caused to rotate together by means of the rod *ap* and toothed wheels at *a* and *p*. At B is the " Bertrand " lens, which renders the interference-figure visible in the eyepiece ; G is the goniometer disc.

With this apparatus a measurement can be obtained, from the first plate, of the apparent acute axial angle in oil, $2H_a$; and from the second plate the apparent obtuse angle in oil, $2H_o$, can be determined in the same way.

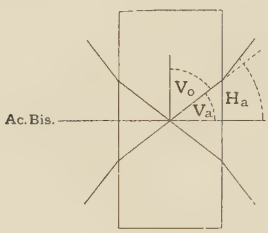


Fig. 386.

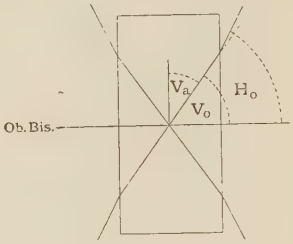


Fig. 387.

Thus if μ be the mean index of refraction of the crystal with respect to the oil, whose refractive index is n, so that

$$\mu = \frac{\text{mean index of the crystal}}{\text{index of the oil}} = \frac{\beta}{n},$$

in the first determination (Fig. 386),

$$\sin H_a = \mu \,.\, \sin V_a,$$

and in the second determination (Fig. 387),

$$\sin H_o = \mu \,.\, \sin V_o ;$$

whence,

$$\frac{\sin H_a}{\sin H_o} = \frac{\sin V_a}{\sin V_o} = \tan V_a,$$

since

$$V_o = 90^\circ - V_a.$$

Thus from the two observed angles H_a and H_o the true axial angle V_a is determined, without any knowledge of μ, from the relation

$$\tan V_a = \frac{\sin H_a}{\sin H_o}.$$

If the index (n) of the oil be known, the mean index of the crystal may then be found from the relation

$$\sin H_a = \mu \,.\, \sin V_a = \frac{\beta}{n} \,.\, \sin V_a ;$$

whence,

$$\beta = n \,.\, \frac{\sin H_a}{\sin V_a}.$$

10. **Relation between the Principal Indices and the Optic Axial Angle.**— If the three principal refractive indices have been measured on the goniometer as described above, the value found by observation for the optic axial angle may be confirmed by calculation from the indices.

From the geometry of the ellipsoid it may be proved that if OA, OB,

OC be its semi-axes, then the angle V between OC and the perpendicular to one of its circular sections is such that

$$\tan V = \frac{OC}{OA}\sqrt{\frac{OB^2 - OA^2}{OC^2 - OB^2}}.$$

But α, β, γ, are the semi-axes of the indicatrix, and the primary optic axes are perpendicular to its circular sections.

Hence,

$$\tan V = \frac{\gamma}{\alpha}\sqrt{\frac{\beta^2 - \alpha^2}{\gamma^2 - \beta^2}},$$

where V is the angle between one of the optic axes and the γ-axis of the indicatrix.[1]

In order to identify a mineral the apparent angle 2E is generally sufficient without the necessity of measuring the refractive indices and the true angle 2V.

In any case, the first process in the case of any crystal is to find the position of the optic axis or axes by trial. This is to be done by examining the crystal in convergent light through pairs of parallel faces, or cleavage-plates, until some portion of the interference-figure can be seen, sufficient to indicate the position of the optic axis or the acute bisectrix.

There may be some difficulty in finding the positions of the optic axes by trial in a crystal, or an angular fragment, or a cut gem, because if an axis emerges very obliquely or near a corner it may be refracted out at such an angle as to lie outside the field of view. This difficulty is obviated by immersing the crystal in an oil, or other liquid of high refractive index, contained in a cell or trough between the condenser and the objective; the rays then emerge from the crystal into a medium of nearly the same refractive index, and are only slightly refracted, and the interference-figure is seen almost as clearly as through a plane section. If the crystal be sufficiently small it may even be immersed in a drop of oil contained between the objective and the condenser. Thus, for example, if the minute pointed summit of a pyramidal crystal of apophyllite, such as one of those from Mexico, be cleaved off and be placed on its cleavage-surface in a drop of cassia oil on a thin glass slip on the microscope stage, so that the fragment is entirely immersed, and if the objective be then lowered until it is in contact with the oil (not with the crystal), a perfect uniaxial interference-figure will be seen, just as clear as that shown by a cleavage-plate of the mineral, although the crystal is viewed directly through the acute apex.

[1] In most minerals the differences $(\gamma - \beta)$ and $(\beta - \alpha)$ are small in proportion to the values of the indices; and in this case it has been shown that the value of V given by the approximate formula, $\tan V = \sqrt{\frac{\beta - \alpha}{\gamma - \beta}}$, differs but little from the true value. Hence, if $(\beta - \alpha)$ and $(\gamma - \beta)$ are equal the axial angle 2V is approximately 90°; if $(\beta - \alpha)$ is less than $(\gamma - \beta)$ the acute bisectrix is γ, and the birefringence is therefore positive; while in the reverse case it is negative.

CHAPTER VIII

THE OPTICAL PROPERTIES OF TWINNED AND PSEUDO-SYMMETRIC CRYSTALS

It was mentioned above that crystals belonging to any system may in their angles approximate very closely to the symmetry of a more symmetrical system; when this is the case the resemblance is frequently made still more close by mimetic twinning; thus in an orthorhombic mineral like aragonite (or witherite), which has a prism-angle nearly equal to 60°, the vertical axis is *nearly* an axis of hexagonal symmetry, and thus may be called an axis of pseudo-symmetry.

When three crystals of aragonite are twinned about the prism-faces and interpenetrate, the resemblance to a hexagonal prism is still more complete. Each crystal may be regarded as derived from the next by a rotation of about 60° round the axis of pseudo-symmetry, and consequently that axis has become *very nearly* a real axis of hexagonal symmetry in the compound crystal. The outlines of the three component crystals are easily distinguishable on cutting a section across the prism parallel to their common basal plane, and examining it in polarised light between crossed nicols; each of the individuals of which the hexagonal plate is composed will then "extinguish" uniformly itself, but not at the same time with its neighbours. Fig. 388 represents a triple crystal of aragonite in which the individuals I and II are twinned together on the prism-face m_2 as twin-plane, *i.e.* m_2 is common to the two crystals; I and III are similarly twinned together on the face m_3. The striations on each individual represent the direction of its brachy-pinakoid {010}. Each of the three individuals is in its position of extinction when these striations are parallel to a cross-wire of the microscope.

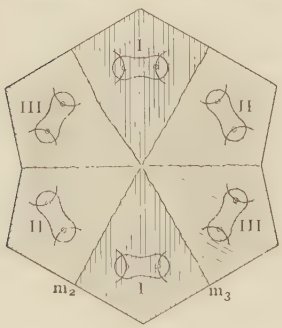


Fig. 388.—Aragonite.

When two plates of crystal overlap, what has been said above concerning the transmission of light through a single crystal no longer holds good, and there is in general no position in which the compound crystal appears dark between crossed nicols. Only when the extinction-lines of the

two plates happen to coincide is there any definite position of extinction. Hence if there be an area where two, or three, of the crystals overlap near the centre of Fig. 388, this will always transmit light as the stage of the microscope is rotated.

Examined in convergent light each of the three individuals will give a biaxial interference-figure in which the plane of the optic axes is parallel to the macro-pinakoid, *i.e.* is perpendicular to the striations of Fig. 388. But in the area where two or more individuals overlap there will be indications of two or three pairs of optic axes visible simultaneously, and the coloured fringes surrounding them will be no longer the regular curves of Fig. 344.

It sometimes happens that the overlapping of a number of biaxial plates whose acute bisectrices coincide gives rise to an interference-figure closely resembling and scarcely to be distinguished from a uniaxial figure. As was shown by Nörrenberg, this effect of overlapping may be studied by superposing cleavage-plates of mica upon each other. If a sufficient number of sufficiently thin plates be piled with their axial planes at right angles to each other, the combination will give an apparently uniaxial interference-figure in convergent light.

When a pseudo-symmetric twin is composed of completely interpenetrant crystals it may be impossible to find any portion which either possesses a definite position of extinction, or yields a definite interference-figure. But in general a thin section of a pseudo-symmetric crystal, when examined by the polarising microscope, will appear to be divided into regular and differently orientated sectors, as in Fig. 388. Now, it has been stated above that crystals belonging to the cubic system are not doubly refracting. It has, however, long been observed that many apparently cubic minerals transmit light between crossed nicols—some in irregular patches, and some in geometrical sectors. For example, a section of the white garnet from Auerbach, cut parallel to (111), shows a regular division into three doubly refracting areas, a section parallel to (100) shows four such areas, while sections parallel to (110) extinguish uniformly.

Such peculiarities have by many been supposed to be due to internal strains set up during crystallisation as a result of cooling, and to be similar to the double refraction of chilled or compressed glass ; and they have been imitated by gelatine models of various crystalline forms which have been cut while moist, so that in the contraction on drying they have been symmetrically strained. They are known as " optical anomalies." In 1876, however, it was shown by Mallard that in many cases these appearances may be explained as the result of mimetic twinning in pseudo-symmetric crystals. An extremely instructive case is that of leucite. This mineral occurs almost invariably in icositetrahedra {211}, which are so characteristic of the mineral that this form is often known by the name of the leucitohedron. It was, however, observed that the crystals are traversed by twin-lamellæ parallel to four faces (D, E) of the dodecahedron ; in Fig. 389 these are (011), (0$\bar{1}$1), (101), ($\bar{1}$01). Now, if a dodecahedral plane is a plane of symmetry it cannot also be a twin-plane ;

the crystals cannot, therefore, belong to the cubic system. Accurate measurements made by vom Rath then showed that the angles are not those of the icositetrahedron {211}, whose faces should be inclined at 48° 11½′; for in leucite the terminal faces O are inclined to each other at 49° 57′, and the lateral faces *i* at 48° 37′; the mineral was therefore regarded as tetragonal, consisting of two forms—the tetragonal bipyramid O {112}, and the di-tetragonal bipyramid *i* {211}—twinned on planes of the tetragonal bipyramid {101} such as the plane *eaf* (Fig. 389).

If this be the case, the mineral, as tetragonal, should be uniaxial. The observations of Mallard and others, however, have shown that, although in parts apparently uniaxial (perhaps owing to the appropriate overlapping of biaxial plates), the crystals are elsewhere biaxial, and therefore cannot possess a symmetry higher than that of the orthorhombic system. In accordance with this it is found that there are in reality also twin-lamellæ parallel to the remaining "dodecahedron"-faces (110), (1$\bar{1}$0) at F; the crystal must therefore be regarded as orthorhombic but referable to three *nearly* equal rectangular axes. The two lateral axes are so nearly equal that angular measurements alone are not sufficient to disprove the apparently tetragonal symmetry.

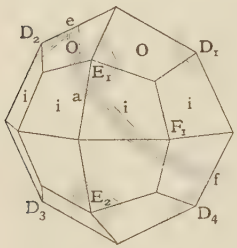


Fig. 389.—Leucite.

In leucite the crystals are traversed by so numerous and fine twin-lamellæ that it is difficult to obtain at any point, in convergent light, the biaxial figure of a single homogeneous crystal.

Fig. 390 represents a section of leucite, cut parallel to (001) and viewed

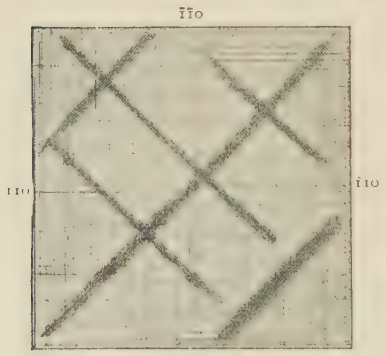


Fig. 390.—Leucite, Section (001).

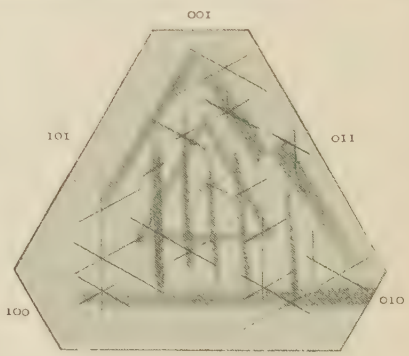


Fig. 391.—Leucite, Section (111).

between crossed nicols. The broad bands denote the twin-lamellæ parallel to the four pairs of dodecahedron-faces which are inclined to the section, *viz.* (101) (011) ($\bar{1}$01) (0$\bar{1}$1), and the fine bands those parallel to the two pairs of dodecahedron-faces (110), (1$\bar{1}$0) which are perpendicular to the section. Fig. 391 is a section cut parallel to (111) and exhibits the same twin-lamellation.

Boracite, again, is apparently cubic and tetrahedral in symmetry; but thin sections parallel to the three cube-faces show that the mineral is really biaxial; each such section is perpendicular to an optic axis of each of four component biaxial crystals. When viewed through a homogeneous patch which is not traversed by twin-structures, boracite gives the biaxial interference-figure of a mineral having an axial angle of about 90°. A boracite crystal is therefore composed of six or twelve pseudo-cubic "sub-individuals," which interpenetrate each other more or less completely and have their bisectrices perpendicular to the dodecahedron-faces. The structure is similar to that shown in Fig. 263.

Now, one of the most singular facts concerning these and some other pseudo-cubic crystals is, that at a certain temperature they lose their double refraction and become suddenly isotropic; that is to say, belong really to the cubic system. Leucite becomes isotropic at a temperature near 700° C.; boracite becomes isotropic at a temperature of 265°; each crystal on cooling regains its former pseudo-symmetric character, although the boundaries of the various individuals are usually found to have changed their original positions. Leucite and boracite are thus examples of the substances described on p. 241 as polymorphous, or capable of forming crystals of two distinct kinds, which are stable at different temperatures.

Leucite occurs in volcanic lavas and must therefore have been formed at a high temperature, as a normal cubic crystal. On cooling it has then been transformed into the pseudo-cubic modification in which it is found.

Boracite may possibly have been formed in the same way, as a cubic crystal; though, from the nature of the minerals usually associated with it, it does not appear likely that it was formed at a high temperature. Investigation has shown that in reality the majority of apparently cubic minerals are doubly refracting and ought perhaps to be regarded as pseudo-symmetric; and it is quite possible that, like other pseudo-symmetric crystals, they may have originally grouped themselves by twinning into mimetic crystals. Some of them, like leucite and boracite, may also be capable of existence in a truly cubic modification, but in others there is no evidence of this. The only common cubic minerals in which so-called optical anomalies are not usually apparent are spinel and cuprite.

In leucite, as we have seen, the pseudo-symmetric character is sometimes betrayed by the external form; each face is not a plane reflecting surface, but is broken up into striæ which belong some to one crystal and some to another.

This is an instance of those cases mentioned on p. 109 in which facets resembling vicinal faces are due to pseudo-symmetric twinning.

It has been found that when leucite is raised to a sufficiently high temperature, not only does it lose its double refraction but all the striæ which accompany the twinning disappear at the same time and the faces of the icositetrahedron become smooth and plane. The indications of twin-structure reappear together with the double refraction when the crystal cools.

Pseudo-symmetric twinning is also to be found among minerals simulating the symmetry of other systems than the cubic, such as aragonite and witherite (pseudo-hexagonal). Apophyllite and vesuvianite (pseudo-tetragonal ?), and mimetite (pseudo-hexagonal ?) are by some also considered as examples. In form these are tetragonal, or hexagonal, but the crystals generally consist of biaxial material, although some specimens give a uniaxial interference-figure. Here, however, as in garnet (p. 569), it is also possible that the anomalous optical characters may be due to strain caused by isomorphous mixture.

In the remaining systems these features are more difficult of proof, since it is far more difficult to distinguish between the biaxial interference-figures of an orthorhombic and a monoclinic crystal than between a biaxial and uniaxial figure. It is not improbable, however, that potash-felspar, occurring as the minerals orthoclase and microcline, which are referred respectively to the monoclinic and anorthic systems, may present an instance of pseudo-symmetric twinning of anorthic material, as indicated on p. 268.

A very remarkable effect is produced by the overlapping of uniaxial crystals which rotate the plane of polarisation, such as quartz. If a basal section of left-handed quartz be laid upon a basal section, of equal thickness, of right-handed quartz, the interference-figure produced by the compound plate consists no longer of circular rings but of right-handed spirals. If the plates be interchanged so that the transmitted light enters the left-handed crystal first, the figure will consist of similar but left-handed spirals. These figures, which are known from the name of their discoverer as Airy's spirals, are often to be seen in a basal section of a quartz crystal, indicating that the crystal is really a twin of right- and left-handed individuals.

It was shown by Reusch that the rotatory polarisation of quartz may itself be imitated by a pile of thin plates of biaxial mica, of equal thickness, arranged like the steps of a spiral staircase, so that the axial plane of each plate is inclined at 120° to that of the one below it. Such a " Reusch combination " rotates the plane of polarisation and gives an interference-figure like that of quartz, Fig. 365.

BOOK II

THE GENERAL PROPERTIES OF MINERALS

CHAPTER I

THE GENERAL PHYSICAL PROPERTIES

1. **Specific Gravity.**—By the *density* of a mineral, expressed in any system of units, is meant the mass of unit volume; *i.e.* in the metric system, the mass in grams of 1 cubic centimetre of the mineral.

The *relative density* of a mineral with regard to water, *i.e.* the ratio of its density to that of distilled water at 4° C., is its *specific gravity*; this is measured by comparing the weight of any volume of the mineral with the weight of an equal volume of distilled water at 4°; the ratio of the former to the latter is the specific gravity of the mineral. If, for instance, a fragment weighs half as much as an equal volume of water at 4°, the specific gravity is 0·5; if it weighs exactly as much as an equal volume of water at 4°, the specific gravity is 1·0; if twice as much, the specific gravity is 2·0.

The specific gravity of a mineral is commonly expressed by the letter G; being merely the ratio of two densities, it is independent of the units employed.

In the metric system the mass of unit volume of water at 4° C. is taken as the unit of mass, so that the density of a body is expressed by the same number as its specific gravity.

The specific gravity of minerals varies between 23·0 (iridium) and 1·44 (natron). Apart from the native metals, the metallic minerals (sulphides, etc.) range mostly from 4·0 (blende) to 10·0 (dyscrasite); but the remainder (oxygen salts) lie mostly between 2 and 5, except those which contain a large proportion of heavy metals (see pp. 626-631).

There are three methods by which the specific gravity may be determined with accuracy, *viz.*: (*a*) hydrostatic weighing; (*b*) the use of the pycnometer; (*c*) the use of heavy liquids.

The first requires a considerable mass of the substance (not less than 1·5 to 2·0 grams), which must, moreover, be free from internal cavities; the second is applicable even when less than 1·5 gram is available, but cannot be used for very small masses (less than 0·2 gram); the third requires not more than the minutest fragments, but cannot conveniently be used for minerals whose specific gravity is greater than 3·3.

(*a*) *Hydrostatic Weighing.*—The mineral is suspended by a fine hair or thread from one end of the beam of a chemical balance (the thread

having previously been counterpoised); it is weighed first in air and then in distilled water contained in a beaker so placed that the mineral is completely immersed in it.

If W = the weight in air, and w = the weight in water, then $W - w$, the loss of weight in water, is equal to the weight of the displaced liquid, *i.e.* the weight of an equal volume of water. The specific gravity is therefore approximately $\frac{W}{W-w}$.

For an accurate determination, however, account must always be taken of the temperature of the water, and its diminished density. If the density of water at the temperature of observation ($t°$) be Δ_t (that of water at 4° C. being unity), the weight of water displaced at 4° C. would be $(W-w) \cdot \frac{1}{\Delta_t}$, and the specific gravity will be

$$G = \frac{W}{W-w} \cdot \Delta_t.$$

The discussion of other corrections to be applied where extreme accuracy is desired, and of the best methods of weighing, will be found in text-books of physics. Of far more importance in the practical determination of the specific gravity of minerals is the selection of pure material, and the precaution that there shall be no air bubbles adhering to the surface of the mineral when it is weighed in water. The influence of intermingled impurities or of internal cavities in such large masses of mineral as are required for this method will often far exceed the correction for temperature. On this account the methods described below, under (*c*), are to be particularly recommended, as a minute fragment only of the mineral is required. The effect of cavities or adherent bubbles is to give too low a value for the specific gravity. The bubbles can be partly removed by brushing them from the surface of the mineral when it is immersed; but the only way in which they can be completely eliminated is by boiling the water with the mineral in it for about half an hour, or by keeping the beaker containing the water and immersed mineral for the same length of time under the exhausted receiver of an air-pump.

(*b*) *The Pycnometer.*—This instrument, which is also known by the name of "the specific gravity bottle," is a small flask of glass with a narrow neck, having a ground glass stopper carrying a thermometer; it is also provided with a bent capillary side-tube bearing a fine mark near its upper end, which can be closed with a glass cap (Fig. 392). The weight of the empty pycnometer is first determined. The mineral, having been broken up into small fragments about the size of very small shot, is then introduced into the pycnometer and weighed. The pycnometer containing the mineral is next partially filled with distilled water, which is then boiled for some time to expel all air bubbles. It is then cooled to the temperature of the room, filled up with boiled water, and the stopper inserted. The bottle is then immersed up to its neck in a large vessel of water at a known temperature $t°$ slightly above that of the room. This

causes the water to expand and overflow through the capillary tube. When the water in the bottle has reached $t°$ the level of the water in the capillary tube is brought down to the mark with a slip of filter paper. The bottle is then removed and carefully dried outside, care being taken not to warm it by handling. It is then weighed again. (If the mineral be too finely powdered some difficulty will be experienced in making it sink to the bottom of the water.)

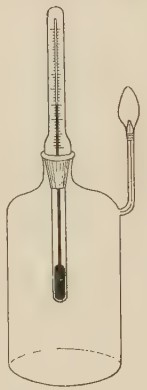


Fig. 392.—Pycnometer.

Finally, the pycnometer is emptied and refilled with water, the same precautions being observed as in the last operation, and when the column in the capillary tube is reduced to the same height as before, the pycnometer is weighed again.

If W = weight of the pycnometer containing the mineral, W_1 = weight of the pycnometer containing both water and the mineral, W_2 = weight of the pycnometer containing water alone, and P = weight of the pycnometer; then $W - P$ = weight of the mineral in air; $(W_2 - P) - (W_1 - W)$ = weight of the water displaced; and the specific gravity is approximately

$$G = \frac{W - P}{(W_2 - P) - (W_1 - W)}.$$

If account be taken of the diminished density Δ_t of water at $t°$, then, as before, the specific gravity is

$$G = \frac{W - P}{(W_2 - P) - (W_1 - W)} \cdot \Delta_t.$$

It is very important in using the pycnometer to make sure that the outside is thoroughly dry; the stopper may be slightly greased to prevent any escape of water round its sides.

With due precautions this method is susceptible of great accuracy, and the specific gravity determined with a weight of one gram may be fully relied upon to the third decimal place, provided that a sufficiently small pycnometer be used. The crushing of the mineral into small fragments eliminates to a great extent any error due to internal cavities or enclosed impurities in the material.

(*c*) *Heavy Liquids.*—If a particle of rock-crystal, whose specific gravity is 2·65, be immersed in a liquid of exactly the same specific gravity, it will neither float nor sink, but will remain suspended at any point within the liquid. The slightest increase in the density of the liquid will cause the particle to rise; the slightest decrease will cause it to sink.

To secure this result a liquid is required of greater density than 2·65, but one which is capable of dilution, so that its density may be reduced to the required extent. The exact specific gravity of the mineral can then be determined by finding that of the liquid when it has been so diluted that the mineral remains suspended in it. The specific gravity

of the liquid may be found by means of the pycnometer, or more conveniently by means of the Westphal balance, as described below.

The most convenient liquid to use is methylene iodide, which is a clear, transparent, brownish liquid, having the specific gravity 3·3 (the mineral dioptase remains exactly suspended in the undiluted liquid); it may be diluted to any extent with benzene, so that a liquid having any specific gravity between 3·3 and 0·98 (the specific gravity of benzene) may be obtained. Care must be taken that the mixed liquids are well stirred so as to ensure a uniform density. The liquid may be contained in a small glass tube, and the minutest fragments of mineral are sufficient.

If the pycnometer is used, it is first filled with the liquid (care being

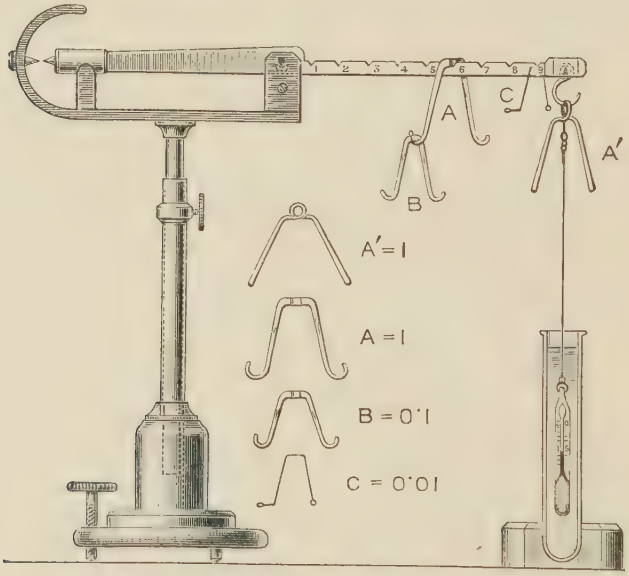


Fig. 393.—Westphal Balance.

taken to avoid change of temperature and loss of the volatile benzene by evaporation) and the level brought to the mark. After weighing it is carefully cleaned, filled with water, adjusted to a known temperature $t°$, and weighed again. If these weights are W_1 and W_2 respectively, P being the weight of the pycnometer, the specific gravity of the liquid is

$$G = \frac{W_1 - P}{W_2 - P} \cdot \Delta_t.$$

The Westphal balance (Fig. 393) has a short beam with unequal arms, the longer of which is divided into ten parts, while the shorter carries a fixed counterpoise. From the longer arm a glass sinker (usually in the form of a small thermometer) is hung by a fine platinum wire, and its weight (in air) is exactly balanced by the counterpoise. When the sinker is immersed in a liquid the weight on the arm will be diminished by the

weight of an equal volume of the liquid, and this weight must be added to the arm to restore equilibrium. The weights are in the form of wire riders, A or A′, which are exactly equal to the weight of water at 4° which is displaced by the sinker.[1] If the sinker is immersed in water at 4° one such rider will restore equilibrium if hung at the end of the arm. If the sinker is immersed in a liquid of specific gravity 2·0, two riders will be required. If the specific gravity be 0·8 a single rider must be placed at division 8 on the arm, and so on. For more exact measurements two smaller riders, B and C, are provided, equal to $\frac{1}{10}$ and $\frac{1}{100}$ of the above unit, which will give respectively the second and third place of decimals. Fig. 393 shows the balance in equilibrium in a liquid of specific gravity 1·669. The specific gravity of a liquid, and hence of a suspended mineral grain, may thus be determined, to three places of decimals, by a single weighing.

In practice heavy liquids are in constant use for identifying a mineral by comparing a fragment of it with others of known specific gravity. Two known minerals of nearly the same density having been found, one of which floats while the other sinks in a liquid in which the mineral under observation remains suspended, it is certain that the latter has a specific gravity between theirs. This is a process of very great value in the determination of minerals, and one which is very easily applied with the help of the table given on pages 626-631.

This method of obtaining the specific gravity of a mineral fragment by comparison with other known minerals has been developed by Sollas in the following manner.

Into a long test-tube is poured a small quantity of methylene iodide, and upon this a suitable quantity of benzene. The tube is then allowed to stand for some hours until the two liquids have formed by diffusion a column whose density gradually increases from the surface downwards, consisting mainly of benzene near the top and mainly of methylene iodide near the bottom. The tube must be tightly corked to prevent evaporation of the benzene.

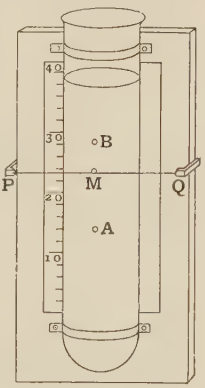


Fig. 394.—Diffusion Column.

A minute fragment of mineral (of specific gravity less than 3·3) being dropped into the tube, remains suspended at a point where the specific gravity of the liquid is equal to its own. Let this be M (Fig. 394).

Now a series of small glass beads or crystals of known specific gravities ranging from 3·3 to 1·0 having been prepared, two of these will be found (by successive trial), one of which (A) remains suspended below, and the other (B) above the mineral fragment M.

A scale divided into equal parts being fixed behind the tube, the distance between B and M can be compared with that between B and A.

[1] If (as is usual) the riders are adjusted for water at 15° C., the reading must be multiplied by $\Delta_{15°}$ (=0·99918) to give the true specific gravity as above defined.

If, then, b be the specific gravity of B, a that of A, and m that of M,

$$\frac{a-m}{m-b}=\frac{\text{AM}}{\text{BM}}, \quad \therefore m=\frac{b\times\text{AM}+a\times\text{BM}}{\text{AB}}.$$

Thus, if AM = 5 divisions, and BM = 2 divisions, if the specific gravity of B be 2·23, and that of A be 2·98, the specific gravity of M is

$$m=\frac{5\times 2\cdot 23+2\times 2\cdot 98}{7}=2\cdot 44.$$

To avoid parallax the scale should be engraved or fixed on a glass mirror fixed behind the test-tube, and the reading should be taken by means of a horizontal wire PQ which can slide in front of the tube, and is viewed so as to coincide with its reflection in the mirror.

The beads may be selected from different kinds of glass or constructed of glass balls or beads made of capillary tubing with platinum wire fused into them, and their specific gravities may be determined by immersing them in a liquid in which they are just suspended, and determining that of the liquid by means of the Westphal balance.

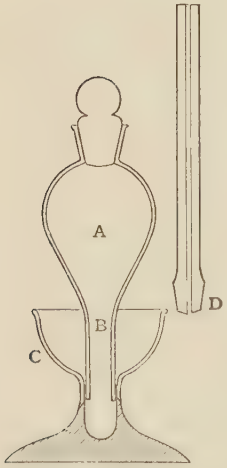


Fig. 395.—Separator.

Heavy liquids are also employed for purifying material for an analysis, or to separate the different minerals in a mixture—a crushed rock, for example—by means of their different densities.

A convenient apparatus for this purpose consists of a pear-shaped glass bulb, A, Fig. 395, ending below in a short tube B, the end of which is ground into a recess in the bottom of a small cup, C, which serves as a stand. The mouth of the bulb can be closed with a stopper, and the opening from it into the tube can also be blocked by a ground glass plug D at the end of a thick-walled capillary tube which serves as a handle. The bulb is placed in the cup and partly filled with the heavy liquid. The coarsely powdered minerals are added and the liquid diluted till the heaviest mineral sinks and passes down through B into the recess in C. The plug is then inserted and the bulb removed from the cup. Any grains remaining in B can be washed out by drawing up a little of the light liquid by sucking through the capillary tube.

Methylene iodide darkens on exposure to light, owing to liberation of iodine, but it may easily be clarified either by freezing the liquid or by shaking it up with a little mercury or potash. This liquid may further be raised to a density of 3·65 by dissolving in it iodoform and iodine.

Another very convenient liquid is acetylene tetrabromide (sp. gr. = 3·0), which can also be diluted with benzene. In either case the pure liquid can be readily recovered by evaporating off the benzene on a water bath. Bromoform (sp. gr. = 2·88) may also be used.

Other heavy liquids have been recommended, such as aqueous solutions of potassium-mercuric iodide (Thoulet's or Sonstadt's solution), spec. grav. = 3·196; of cadmium borotungstate (Klein's solution), spec. grav. = 3·28, (either of which may be diluted with water); and of barium-mercuric iodide (Rohrbach's solution), spec. grav. = 3·58. Of these Klein's solution is the most convenient.

A still heavier liquid, which is useful for separating minerals, is that obtained by fusing thallium-silver nitrate, which melts at 70° to a clear liquid and has a specific gravity near 5; the density may be reduced by dilution with warm water. This liquid cannot, however, be conveniently used for determining specific gravities, owing to the temperature required; and sulphides are liable to be attacked by it.

2. **Specific Heat.**—The specific heat of a mineral is the quantity of heat required to raise the temperature of one gram of the substance through one degree centigrade.

This amount must be measured in certain arbitrary units, and the unit of heat always employed is the amount necessary to raise one gram of water through one degree C.; this is practically constant for each degree, at any rate between the temperatures 10° and 30°.

To determine the specific heat the mineral is broken into fragments and placed in a small wire basket; having been raised to a certain temperature in an air bath (which is generally heated by steam) it is then rapidly immersed in a vessel of water of known temperature, and the rise of temperature produced therein is noted by means of thermometers immersed in the water.

If W = weight of the mineral,
t = initial temperature of the mineral,
W_1 = weight of the water,
t_1 = initial temperature of the water,
T = final temperature of the mineral and the water,
x = specific heat of the mineral,

then $(t-T)Wx$ is the number of units of heat lost by the mineral, and this must be equal to $(T-t_1)W_1$, the number of units of heat gained by the water; the specific heat of water being 1.

Therefore,

$$x = \frac{(T-t_1)W_1}{(t-T)W}.$$

In practice numerous precautions and corrections are required in order to ensure accuracy; allowance must be made for the heat-capacities of the wire cage which carries the mineral, and of the vessel which contains the water; a correction must be applied for radiation during the experiment; and some effective method of stirring the water, so that it acquires a uniform temperature, must be adopted. These will be found described in the text-books of physics.

Experiment has shown that the specific heat of any compound is closely related to those of its constituents. Determinations of the specific heat may therefore be expected to prove of value in the interpretation

of chemical analyses; they have not been applied to any great extent in mineralogy, and the specific heat has never yet been employed for the identification of minerals, like the specific gravity.

3. **Electricity and Magnetism.**—The electrical and magnetic properties of crystals, in particular their electrical conductivity, dielectric constants, and magnetic permeability (or capacity for magnetisation), and the phenomenon of pyroelectricity, vary with direction, and their discussion, as directional properties, therefore strictly belongs to Book I, Chapter V. It may, however, be remarked here that minerals may be roughly classified as "conductors" or "non-conductors" of electricity (or, on the other hand, as "magnetic" or "non-magnetic"), according as their conductivity (or their power of being attracted by a magnet) is marked or negligible.

These properties are sometimes useful in the recognition of minerals (as in the case of magnetite and a few other minerals, which are attracted by a magnet or compass needle), and they can also be applied to the separation of minerals from a mixture.

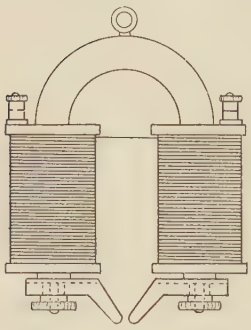


Fig. 396.—Electromagnet for separating Minerals.

For the separation of magnetic from non-magnetic minerals it is convenient to use an electromagnet (Fig. 396) provided with pointed pole-pieces of soft iron. The mixed minerals, in powder, are presented to the magnet poles, when the magnetic constituents adhere to the latter and may afterwards be detached by cutting off the current. By using currents of increasing strength, or by moving the poles nearer together, minerals which are more or less magnetic may successively be separated from those which are entirely non-magnetic.

A similar method has been applied on a large scale to the separation of magnetic from non-magnetic ores, as that of wolfram from cassiterite.

In the separation of conducting from non-conducting minerals in a mixture, advantage is taken of the fact that a conducting particle connected to earth is attracted to an electrified body owing to the charge induced in it, while a non-conductor is not so attracted. The powdered mixture is spread out on a flat metal plate connected to earth, and a similar, insulated plate, covered with shellac varnish and resting on small discs of glass cemented to its corners, is placed over it at a distance of a few millimetres. An electric charge is then given to the upper plate by means of an electrophorus, and the grains of any conducting mineral present in the mixture are attracted and adhere to it, while the non-conducting grains remain unaffected.[1]

A remarkable electrical property possessed by certain crystallised minerals is largely utilised in wireless telegraphy and telephony.

If a contact be formed between a crystal of (say) galena and a metal point or spring pressed against it, and be included in an electric circuit, it

[1] T. Crook, *Mineralogical Magazine*, vol. xv, p. 260; vol. xvi, p. 109.

offers more resistance to the passage of current in one direction than in the other, so that it acts as a " rectifier " by which an alternating current is converted, more or less completely, into an intermittent direct current.

In wireless telegraphy and telephony the alternations of the high-frequency current induced in the receiving circuit by the electromagnetic waves are far too rapid to cause audible vibrations in the telephone; but if a crystal-contact be included in the circuit a direct current is obtained, and if the waves sent out by the transmitter are interrupted at intervals of audible frequency the diaphragm of the telephone is caused to vibrate.

This action of the crystal is doubtless connected with its regular structure and is strictly a directional property, but the cause of it is at present obscure.

Among minerals which have been used in this way as " crystal detectors," may be mentioned galena, pyrite, erubescite, zincite, and anatase.

4. **Radioactivity.** — Certain minerals, especially those which contain uranium and thorium, show very markedly the phenomena which are known under the name of radioactivity.

Certain elements, of which the most important are uranium, thorium, and radium, together with their compounds, are constantly emitting " radiations," which have the property of acting on a photographic plate, of causing phosphorescence in, or changing the colour of, many substances, and of causing the leakage of electricity from a charged body, such as an electroscope, by causing conductivity in the surrounding air.

These radiations can penetrate through a greater or less thickness of matter, and are of three kinds, distinguished as α-, β-, and γ-rays, which differ in their nature and in their power of penetration.

The α-rays, which are least penetrating, and which are stopped by a sheet of aluminium of 0·1 mm. in thickness, or by 7 cm. of air, appear to consist of atoms of helium carrying a positive charge of electricity ("ions") and moving with a very high velocity, about one-fifteenth of that of light.

The β-rays are somewhat more penetrating, but are stopped by a layer of 2 mm. of lead. They are believed to consist of minute negatively charged particles (electrons) travelling with a speed approaching that of light.

The γ-rays can penetrate a much greater thickness, up to several centimetres, of lead. They do not consist of moving particles, but are of the same nature as X-rays, *i.e.* they consist of a wave motion like that of light but of extremely short wave-length.

These radiations are caused by the fact that the atoms of the radioactive elements are continually undergoing spontaneous disintegration, by which they are converted into other elements of slightly lower atomic weight with the separation of helium, which is emitted as α-rays. The elements formed are themselves radioactive, and successively undergo further disintegration with the ultimate formation, in all cases, of lead, which is a stable element; and with its formation the series of changes ends.

Radioactivity was first discovered, by Becquerel in 1896, in uranium

and its compounds, and was afterwards observed, by Mme. Curie, in thorium. The mineral pitchblende, however, was found to be far more strongly radioactive than was to be expected from the amount of uranium it contained, and this led to the discovery in it of the new element, radium, which is one of those formed by the disintegration of uranium, but which is many times more radioactive than uranium.

The gradual accumulation of helium and of lead in radioactive minerals, and also the colour-changes produced in certain minerals round radioactive inclusions (*cf.* p. 573), have been utilised to obtain an estimate of the age of the minerals, *i.e.* the time which has elapsed since their formation; the results vary in rocks of different formations up to as much as 1500 million years (zircon from Mozambique).

CHAPTER II

THE CHEMICAL PROPERTIES

During a great portion of the first half of the last century, the predominant school of mineralogy was that associated with the names of A. G. Werner and F. Mohs, who were successively professors at the Mining Academy of Freiberg in Saxony. This school endeavoured in systematic mineralogy to employ exclusively the so-called "Natural Historical Properties." Werner's lectures, and a well-known treatise which he published on the External Characters of Minerals, were largely devoted to the study of those characters by which minerals can be identified without the aid of chemical tests. And Mohs, in his *Treatise on Mineralogy* (English translation by Haidinger, 1825), especially defines the natural historical properties as "those with which Nature has endowed the bodies which it produces, *provided these properties, as well as the bodies themselves, remain unaltered during their examination.*"

Now, since the chemical characters of any substance may be defined as those which it exhibits during conversion ("chemical change") into some substance which possesses other properties, it is evident that in the hands of these teachers chemistry found little or no application in the study of minerals.

A reaction against such a treatment of the subject was initiated by the influence of Berzelius and the Swedish chemists, and subsequently the chemical properties have come to be held in very different estimation, until at the present time they are regarded as of primary importance.

Modern methods are, of course, totally opposed to the "Natural Historical" spirit in mineralogy; the investigator is bound to examine *all* the available characters of minerals, and among these the chemical composition is quite the most important, whether for purposes of identification, classification, or research.

In seeking to identify a mineral it is generally necessary, and always advisable, to sacrifice a portion in order to ascertain its chemical nature, and to determine by the use of various reagents, or with the help of the blowpipe, at least some of the elements which it contains.

Again, the basis of classification, originating with that of Berzelius, is (broadly) a chemical one, and without the knowledge of the composition it would be impossible to frame any clear conception of the relationships which exist between minerals.

Further, it is from the relations between their chemical and their other properties that the most important advances in scientific mineralogy are to be expected in the future.

A really complete knowledge of the chemical constitution of a mineral, if such be possible, would probably enable us to predict all its other properties.

1. **The Elements in Minerals.**—All the elements which have been isolated by chemists, except the inert gases of the atmosphere (neon, argon, krypton, and xenon), have been found in minerals; many of them are also to be found in animals or vegetables, or in their products; some, like nitrogen, which are of common occurrence among organic substances, are rare among minerals. Carbon, again, which in the form of many different compounds enters into the greater part of organic Nature, is comparatively rare in the mineral kingdom, although contained in one important group of compounds (carbonates). On the other hand, silicon, which is rare among organic materials, is one of the most common constituents of minerals.

It has been estimated that in the materials of the earth's crust are contained about 47 per cent of oxygen, about 27 per cent of silicon, about 8 per cent of aluminium; that iron, calcium, magnesium, sodium, and potassium are present in quantities varying from 6 to 2 per cent; while none of the remaining elements amount to more than $\frac{1}{2}$ per cent. Hence oxygen is by far the most important element in the minerals of the earth's crust.

Apart from gases, comparatively few elements occur in Nature in the uncombined or "native" state; such are carbon, sulphur, arsenic, antimony, bismuth, gold, silver, copper, mercury, tellurium, lead, platinum, iridium, osmium, ruthenium, rhodium, palladium, and iron, and of these the last nine are very rare.

Some of the elements exist as important constituents of only a few minerals, though the minerals in which they occur are not necessarily very rare; such are beryllium, bromine, cadmium, chromium, iodine, lithium, molybdenum, nitrogen, selenium, tin, titanium, uranium, vanadium, zirconium.

The following elements are important constituents of the minerals in which they are usually contained, but the minerals themselves are exceedingly rare cæsium, erbium, germanium, osmium, iridium, scandium, yttrium. The interest of such minerals is mainly due to their being the source of the above rare elements, and it is chiefly for the investigation of such elements and their compounds that these minerals have been sought and studied.

Some elements, again, *e.g.* gallium and indium, are only found in minute proportion in certain minerals, such as blende.

2. **Atomic Constitution of Minerals.**—It is not the purpose of the present chapter to give any account of the principles of chemistry, which are treated in the text-books of that subject; but rather to indicate the chief features of the chemistry of minerals as compared with that of other substances. It will be made clear in a subsequent chapter that the

chief difficulties which beset the study of mineral chemistry are due to the fact that the materials investigated have not been prepared from known compounds in the chemist's laboratory, but have been made by Nature from the vast mixture of materials existing in and beneath the earth's crust, and under widely varying conditions; hence minerals are not in general simple pure compounds, but are for the most part complicated by numerous impurities, or are often, at the best, isomorphous mixtures (see p. 251). To eliminate the impurities, to trace the simple compounds of which these mixtures consist, and to determine the nature and constitution of the species to which they can be referred, is the task of the mineral chemist.

When a substance can, by change of temperature and pressure, be converted from a solid to a liquid, or from a liquid to a gas, and *vice versa* (like ice, water, and steam), it is regarded as retaining its identity in the three states.

It has commonly been assumed that the molecule of the solid is an aggregation of the gaseous molecules, and is to be expressed as a multiple of the latter. Recent research with X-rays seems, however, to indicate that the molecule in a crystal is by no means so large a multiple of the gaseous molecule as was formerly supposed, and in many cases they may probably differ very little, though we are not at liberty to assume that they are identical.

In some crystals, even, it would seem that the atoms are so arranged that there is no natural grouping of them into molecules, or at least that the atoms belonging to a given molecule are no nearer together than those of two adjacent molecules, so that a grouping of the atoms of the crystal into molecules becomes arbitrary. (Compare the structures of salt, diamond, etc., p. 288.)

The formula of the gaseous molecule itself, commonly known as the "molecular formula" of the substance, might be ascertained if the vapour-density of the mineral could be found; but almost all minerals are solids which cannot be vaporised, so that little or nothing is known yet of their gaseous molecules, and even if the molecular formula were known it would not necessarily explain the constitution of the crystallised mineral.

The formulæ by which minerals are denoted indicate, therefore, as a rule, little more than the relative proportions of the elements which they contain, and are merely an expression of the percentage composition as determined by analysis, translated into the language of atomic proportions.

Thus barytes is denoted by the formula $BaSO_4$, which (since the atomic weight of barium is (approximately) 137, that of sulphur 32, and that of oxygen 16) indicates that the mineral consists of these three elements in the following proportions by weight:

Ba	137	or, in percentages,	Ba 58·8
S	32		S 13·7
O	64		O 27·5
	233		100·0

Such a formula, which denotes no more than the relative proportions of the elements, and is therefore only sufficient to give the theoretical percentage composition of a mineral corresponding to its analysis, constitutes the "empirical formula."

From the percentage composition, as given by quantitative chemical analysis, the empirical formula is found by dividing the percentage of each element by its atomic weight, thus for barytes:

$$\frac{58{\cdot}8}{137} = {\cdot}429\,; \quad \frac{13{\cdot}7}{32} = {\cdot}429\,; \quad \frac{27{\cdot}5}{16} = 1{\cdot}7187.$$

The numbers of atoms of barium, sulphur, and oxygen in the molecule are therefore in the proportion of ·429 : ·429 : 1·7187 = 1 : 1 : 4; so that the empirical formula is $BaSO_4$.

The law of definite combining proportions is now so well established that no doubt can be entertained of the possibility of referring every pure compound to a definite empirical formula like the above. It will be found, however, that few analyses of minerals lead to simple formulæ, or even to definite atomic proportions. This is often partly due to the difficulty of obtaining the mineral free from enclosed impurities, but even more frequently to the fact that compounds which are nearly related to one another in composition and in crystalline form can crystallise together in varying proportions to form homogeneous crystals ("isomorphous mixtures") as described below in Book III, and that most minerals consist of a mixture of two or more simple compounds in this way. The difficult problem which has to be solved by the mineral chemist is the reduction of widely varying and complicated analyses to simple atomic proportions and simple empirical formulæ. This has been so successfully accomplished for some complex minerals (such as tetrahedrite, pyroxene, felspar) that we may expect with perfect confidence the ultimate reduction of all mineral species to definite, and probably also to simple, formulæ.

3. **Equivalence of Atoms in Minerals.**—Confining our attention for the present to those minerals whose analyses lead to definite simple formulæ, we find on comparing their empirical formulæ that many of them are similar and only differ in having a certain number of atoms of one element in the one substituted for a certain number of atoms of another element in the other; thus barytes, $BaSO_4$, is related to anglesite, $PbSO_4$, and both are related to sodium sulphate (thenardite), Na_2SO_4, and to sulphuric acid, H_2SO_4; one of the compounds may be considered as derived from another by the interchange of the atoms, or atomic groups, Ba, Pb, Na_2, H_2, and these groups are said to be equivalent to one another.

Generally speaking, two atoms of a "monad" element, such as hydrogen, may replace one of a "dyad" element, such as barium; three of a "dyad" element may replace two of a "triad," and so on, to form a series of compounds which may conveniently be classed together; in this instance as "sulphates." Elements are therefore distinguished as "monovalent," "divalent," "trivalent," etc., according to the number of atoms of hydrogen which one atom of the element can replace, or with

which it can combine. The " valency " of an element may be indicated in its symbol, thus : H′, Ba″, Al‴, Si⁗, etc.

Further observation shows, however, that in minerals, as in other compounds, the valency of an element is not always the same ; it may, for instance, in one substance act as a triad, and in another as a dyad, so that it may form two distinct series of compounds. The most conspicuous example is iron, which may occur either in the ferrous (divalent) or the ferric (trivalent) condition.

It is important, then, in comparing the chemical characters of different minerals to base their classification upon the nature of the elements which they contain. For different purposes in mineralogy it is convenient to distinguish the elements as metallic and non-metallic, or as electro-positive and electro-negative (although the latter terms can only be used in a relative sense), or to group them according to their valencies as monads, dyads, etc. ; but for the purpose of classifying minerals the mineralogist generally uses the classification of the elements, which was introduced by Mendeléev.

The advantage of this classification depends upon the fact that the properties, both physical and chemical, of the several elements (apart from certain exceptions), vary regularly in a periodic manner with the atomic weight ; so that if the elements are arranged in a series, in order of increasing atomic weight, the properties of the lighter elements are found to be similar to those of other elements further on in the series.[1]

Thus, in the accompanying table, the elements which fall into the same vertical column resemble one another in their properties and are said to belong to the same " group " (numbered from 0 to VIII). Within a given group a still closer relation exists between those elements which are placed vertically under one another in the table, and a group thus consists of two sub-groups. Corresponding compounds of elements belonging to such a sub-group (*e.g.* K, Rb, Cs) are very closely related in their properties and have been called " eutropic."

Since the most closely allied elements occur at corresponding places in

[1] The so-called " metals of the rare earths " (lanthanum, cerium, etc., fifteen in number), form an exception to this rule ; and in the three pairs of elements : argon and potassium, cobalt and nickel, tellurium and iodine, the order of the atomic weights must be reversed in order to bring these elements into their proper positions in the table as indicated by their properties.

The researches of H. G. J. Moseley on the spectra of the X-rays emitted by the various elements when exposed to the electric discharge have led (upon purely physical grounds) to the arrangement of the elements in a continuous series, and the number expressing the position of each element in this series is known as its " atomic number."

The order of the atomic numbers agrees precisely with that of the elements in the periodic table, modified as above, and consequently corresponds still more closely with the chemical properties than does the order of the atomic weights.

The atomic numbers are given in brackets in the table.

A small number of gaps in the series of atomic numbers still remains ; and one such gap has quite recently been filled by the discovery, in a specimen of a zirconium mineral from Norway, of a new element—No. 72, to which the name hafnium has been given. This appears to be allied to zirconium and titanium, and finds a place in Group IV of the table.

The rare earth-metals (Nos. 58 to 71) which follow lanthanum closely resemble this metal in their properties, and must be placed with it in Group III. They thus form a break in the periodicity, and are omitted from the table. The most important of them are cerium and didymium.

PERIODIC TABLE OF THE ELEMENTS

Series.	Group 0	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII	Group VIII
1		H (1) 1·008							
2	He (2) 4·00	Li (3) 6·94	Be (4) 9·02	B (5) 10·82	C (6) 12·00	N (7) 14·01	O (8) 16	F (9) 19·0	
3	Ne (10) 20·2	Na (11) 23·00	Mg (12) 24·32	Al (13) 26·97	Si (14) 28·06	P (15) 31·03	S (16) 32·06	Cl (17) 35·46	
4	Ar (18) 39·91	K (19) 39·10	Ca (20) 40·07	Sc (21) 45·1	Ti (22) 48·1	V (23) 51·0	Cr (24) 52·0	Mn (25) 54·9	Fe (26), Co (27), Ni (28) 55·8 58·9 58·7
5		(29) Cu 63·6	(30) Zn 65·4	(31) Ga 69·7	(32) Ge 72·6	(33) As 75·0	(34) Se 79·2	(35) Br 79·9	
6	Kr (36) 82·9	Rb (37) 85·4	Sr (38) 87·6	Y (39) 88·9	Zr (40) 91·0	Nb (41) 93·1	Mo (42) 96·0	— (43)	Ru (44), Rh (45), Pd (46) 101·7 102·9 106·7
7		(47) Ag 107·9	(48) Cd 112·4	(49) In 114·8	(50) Sn 118·7	(51) Sb 121·8	(52) Te 127·5	(53) I 126·9	
8	Xe (54) 130·2	Cs (55) 132·8	Ba (56) 137·4	La (57), etc. 138·9	Hf (72) 180·8	Ta (73) 181·5	W (74) 184·0	— (75)	Os (76), Ir (77), Pt (78) 190·8 193·1 195·2
9		(79) Au 197·2	(80) Hg 200·6	(81) Tl 204·4	(82) Pb 207·2	(83) Bi 209·0	(84) Po	(85) —	
10	Nt (86) 222·0	— (87)	Ra (88) 226·0	— (89)	Th (90) 232·2	— (91)	U (92) 238·2	—	

the table, it is not surprising to find that the latter also indicates many remarkable analogies between mineral compounds. Minerals which are corresponding compounds of elements belonging to a given group often exhibit a great similarity to one another, and the similarity is most marked where the elements fall into the same sub-group.

Thus certain minerals containing magnesium, calcium, zinc, strontium, cadmium, and barium are closely allied; but the corresponding compounds of calcium, strontium, and barium resemble each other far more closely than they resemble those of magnesium, zinc, and cadmium (see the Barytes Group, the Calcite Group, the Aragonite Group, in Part II).

The horizontal rows in the table are known as "series," and if these be numbered it will be noticed that with the exception of carbon and the so-called transitional elements of Group VIII, all the elements mentioned above as occurring native (or uncombined) belong to the odd series. Again, the well-defined groups of minerals frequently described as "metallic" (most of them having a metallic lustre) are almost exclusively either native metals or compounds of the metals Cu, Zn, Ge, Ag, Cd, Sn, Au, Hg, Tl, Pb, belonging to the odd series, or of the transitional elements of Group VIII, Fe, Co, Ni, etc., combined with sulphur, selenium, or tellurium, or with the three allied elements, As, Sb, Bi.

Many other mineralogical relations are disclosed by this table, and are illustrated by the part which the different elements play in the composition of the various minerals to be subsequently described (see p. 245).

Some of the most distinct groups of elements which are of importance in relation to mineralogy are:

In Group	I	(1) the alkali metals, Li, Na, K.
		(2) the metals Cu, Ag.
In Group	II	(1) the metals of the alkaline earths, Ca, Sr, Ba.
		(2) the metals Zn, Cd.
In Group	IV	(1) the elements Si, Ti, Zr.
		(2) the elements Ge, Sn.
In Group	V	(1) the elements P, V, As; and again As, Sb, Bi.
		(2) the elements Nb, Ta.
In Group	VI	(1) the elements S, Se, Te.
		(2) the elements Mo, W.
In Group	VII	the halogen elements, F, Cl, Br, I.
In Group	VIII	the metals Fe, Co, Ni.

In addition to these, certain other elements are found to resemble one another in some of their compounds, though their relationships do not find expression in the periodic table; for example, (1) Sr, Ba, Pb; (2) Mg, Fe″, Mn; (3) Fe‴, Cr, Al. Examples of such relationships will be found below, in the next book (p. 241).

4. **Equivalence of Radicals in Minerals.**—In compounds which consist of more than two elements, as is the case with most minerals, the atoms may conveniently be regarded as associated to form separate groups, which, like the elements, are capable of replacing one another in

different compounds. These atomic groups or "radicals," like the elements, have been distinguished as electro-positive and electro-negative, and each has a certain valency; they may be regarded as replacing each other, or as replacing elements of the same valency. Thus in sal-ammoniac, NH_4Cl, as compared with rock salt, NaCl, the atomic group NH_4 may be regarded as a monad radical, and capable of replacing the metal sodium in combination with the halogen element chlorine. In calcite, $CaCO_3$, and anhydrite, $CaSO_4$, the CO_3 and SO_4 may be regarded as dyad radicals, each capable of combining with the dyad element Ca, or of replacing an atom of the dyad oxygen in CaO.

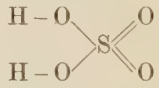
A compound radical (so-called to distinguish it from an element) is generally supposed to consist of several atoms so combined that one or more of their combining capacities or "bonds" are unsatisfied, and the valency of the radical is determined by the number of unsatisfied bonds; thus hydroxyl, H—O—, is a monad radical, and one of great importance in the chemical structure of minerals.

Formulæ which show how the atoms may be grouped together to form certain radicals are called "constitutional" formulæ; and when the formula indicates by means of bonds the mode in which the atoms are supposed to be linked together by their combining capacities, it is called a "structural" or "graphic" formula; thus, for sulphuric acid:

Empirical formula: H_2SO_4 [1]

Constitutional formula: $SO_2(OH)_2$

Graphic formula:



The radicals whose existence is assumed in order to explain the constitution of most minerals are either hypothetical, or are founded upon experiments with other compounds, both inorganic and organic, in the laboratory, and the graphic formula in many cases is based upon very slight evidence. Nevertheless such formulæ are used very generally to indicate possible relations between minerals having similar characters.

5. **Classification of Minerals by Acid Radicals.**—Minerals are classified into certain large divisions or classes, according to their chemical composition, as follows:

1. Elements.
2. Haloid compounds, in which metallic elements are combined with the halogen elements, fluorine, chlorine, bromine, and iodine.
3. Sulphides, arsenides, etc., in which metallic elements are combined with sulphur, arsenic, or allied elements.

[1] The empirical formula is sometimes written in the form $H_2O \cdot SO_3$, in view of the fact that sulphuric acid may be formed from the combination of sulphur trioxide and water, though without implying that these substances are present in the compound.

Formulæ of this type were formerly much used for minerals which are salts of oxy- or sulpho acids: *e.g.* barytes, $BaO \cdot SO_3$; titanite, $CaO \cdot TiO_2 \cdot SiO_2$; proustite, $3Ag_2S \cdot As_2S_3$. They form a convenient way of indicating the empirical composition, derived from analysis, but must not be taken as expressing any view as to the constitution of the molecule.

4. Sulpho-salts, which may be derived from certain sulpho-acids (see Art. 8).
5. Oxides and hydroxides, in which metallic elements are combined with oxygen or with hydroxyl, OH, respectively.
6. Oxy-salts, which may be derived from certain oxy-acids; the most important of these are the carbonates, sulphates, phosphates, and silicates (see Art. 8).

Apart from the native elements, minerals are thus classified according to the non-metallic elements or radicals which they contain.

Each of these classes of minerals contains a number of smaller groups, to be considered below (p. 243).

The terms acids, bases, and salts are freely used in mineral chemistry in the commonly accepted sense, though without the experimental basis upon which the distinctions have been made in the case of the more tractable compounds familiar to chemical students.

In an oxy-acid the hydrogen, which is capable of being replaced by metals or by compound radicals to form a salt, is supposed to be present as a constituent of hydroxyl, OH; and in a sulpho-acid the replaceable hydrogen is supposed to be present as a constituent of the radical SH.

A mineral such as barytes is thus intelligibly described as a salt of sulphuric acid, $SO_2(O_2H_2)$, in which the two atoms of hydrogen have been replaced by one of the dyad metal barium: $SO_2(O_2Ba)$.

All the silicates are oxy-salts, and are referred to certain silicic acids; these should be distinguished in the usual way as monobasic when there is only one replaceable hydrogen atom; dibasic when there are two, and so on; but in reality very little is known of the nature or even of the existence of these acids.

Again, the term "base" is used to signify the oxide of the metallic element in an oxy-salt; but it is not always possible to say whether a given element, especially one of those situated in the central columns of the periodic table, is to be regarded as playing the part of a base or an acid in a given mineral. This is especially true among the large and important group of silicates of aluminium, boron, titanium, zirconium (and tin), concerning which opinions have been much changed during recent years, so that these elements have come to be regarded as forming part of the acid radical in many minerals in which they were formerly considered as bases.

The following are some of the chief acids required to make the composition of the more important minerals intelligible; the salts derived from them receive their names from the radical which the acid contains.

Sulpho-acids—

$As(SH)_3$, or H_3AsS_3, from which are derived (ortho-)sulpharsenites; and the corresponding compounds of antimony and bismuth.

Oxy-acids—

$NO_2(OH)$, or HNO_3, from which are derived nitrates.

$CO(OH)_2$, or H_2CO_3, from which are derived carbonates.

$SO_2(OH)_2$, or H_2SO_4, from which are derived sulphates; and the corresponding compound of chromium (giving chromates).

$WO_2(OH)_2$, or H_2WO_4, from which are derived tungstates; and the corresponding compound of molybdenum (giving molybdates).

$AlO(OH)$, or $HAlO_2$, from which are derived aluminates; and the corresponding compounds of iron and chromium.

$BO(OH)$, or HBO_2, from which are derived (meta-)borates.

$PO(OH)_3$, or H_3PO_4, from which are derived (ortho-)phosphates; and the corresponding compounds of arsenic and vanadium (giving arsenates and vanadates).

$Si(OH)_4$, or H_4SiO_4, from which are derived (ortho-)silicates; $SiO(OH)_2$, or H_2SiO_3, from which are derived (meta-)silicates; } and corresponding compounds of titanium and zirconium.

$TaO_2(OH)$, or $HTaO_3$, giving rise to (meta-)tantalates; and the corresponding compound of niobium.

The following important inorganic salts are scarcely or not at all represented among minerals: chlorates, chlorites, sulphites, thiosulphates, arsenites, nitrites, phosphites; also phosphides, carbides. Owing to the conditions under which minerals exist in the crust of the earth, such unstable or soluble compounds as these, if they are occasionally formed by natural processes, can scarcely survive as minerals, but are quickly decomposed or carried away in solution. The last two have been found in meteorites, which have probably been formed under very different conditions.

6. **Normal, Acid, and Basic Salts.**—The salts derived from any of the acids mentioned above are further grouped into three subdivisions. The first, or normal salts, are those in which all the replaceable hydrogen of the acid is replaced; thus barytes, $BaSO_4$, is a normal salt of sulphuric acid, H_2SO_4; calcite, $CaCO_3$, is a normal salt of carbonic acid, H_2CO_3.

The acid salts, on the other hand, are those in which only a part of the hydrogen of the acid is replaced; thus misenite, $KHSO_4$, is acid potassium sulphate, having only half the hydrogen of the acid replaced by potassium.

Basic salts are such as contain more metallic atoms than are required to replace the hydrogen of the acid. Thus malachite $(CuOH)'_2CO_3$, and chessylite, $Cu''(CuOH)'_2(CO_3)_2$, are both basic copper carbonates. The combining capacities of the metallic atoms may here be supposed to be partly satisfied by hydroxyl, or in some cases by oxygen as in cyanite, $(AlO)'_2SiO_3$.

Acid salts are rare among minerals, except perhaps among the silicates, but instances of basic salts are common.

7. **Molecular Compounds: Water of Crystallisation.**—In some minerals the composition is conveniently expressed as the association of two or more distinct molecules united by some connection different from that which unites the atoms or radicals in each molecule. This is often described as the "residual valency" of the molecules. Compounds of this nature are called "molecular compounds" or "double salts."

Thus kalinite or potash alum, of which the empirical formula is $KAlS_2H_{24}O_{20}$, is often regarded as a molecular compound, and expressed

by the formula $Al_2(SO_4)_3 . K_2SO_4 . 24H_2O$; this suggests that the potassium sulphate, the aluminium sulphate, and the water exist as such in the compound, and are not united exactly as the radicals within each of the three groups, but in some other way. In the case of kalinite this view receives some support from the fact that in a solution of the salt the two sulphates may be separated by the mechanical process of diffusion. On the other hand, this experiment only indicates that the two sulphates are separated in the state of *solution* ; the molecular formula, while possibly representing the nature of the substance in solution, does not necessarily represent that of the molecules of the alum crystal.

Many of the basic salts may with equal propriety be described as molecular compounds ; *e.g.* malachite as $CuCO_3 . Cu(OH)_2$. Other instances of minerals which are often regarded as double salts are cryolite, $3NaF . AlF_3$; matlockite, $PbCl_2 . PbO$; glauberite, $Na_2SO_4 . CaSO_4$; dolomite, $CaCO_3 . MgCO_3$. Most of these may, however, also be expressed as ordinary atomic compounds, *e.g.* dolomite : $O=C\begin{matrix}O-Ca-O\\ \diagdown\quad\quad\diagup\\ O-Mg-O\end{matrix}C=O$.

The distinction between a molecular compound and an atomic compound is only to be established by experiments upon the behaviour of the substance in solution,—experiments which can rarely be made upon minerals.

At the present time there is very little evidence to prove whether any given mineral is to be regarded as a molecular compound or not.[1]

When, however, one or more of the molecules in such a compound are molecules of water, it is possible to a certain extent to invoke experimental evidence and to draw a distinction. Many minerals yield water when heated ; now this may either be present as such in the mineral or it may result from the combination of hydrogen and oxygen contained in the mineral, and be formed on the breaking up of the molecule by heating.

Salts which yield water are said to be " hydrated " ; those which do not yield water are called " anhydrous." The term hydrated is sometimes confined to those which contain water as such.

Sometimes the water is given off at a temperature below 100° ; some-

[1] The constitution of some of the more complex minerals, particularly basic salts, is perhaps best explained on the basis of Alfred Werner's " co-ordination theory," which is an extension of the idea of residual valencies mentioned above. According to this theory certain atoms or groups of atoms are united to a central atom by so-called " supplementary valencies " to form a group or " nucleus," to which other atoms are attached by the ordinary or " principal " valencies.

In soluble compounds the nucleus on the one hand and the external atoms on the other are split apart to form the ions in a solution. The atoms or groups within the nucleus are said to be " co-ordinated " with the central atom. They are not ionised in a solution, and their presence is therefore not detected by the ordinary chemical tests. For example, a solution of potassium chloroplatinate K_2PtCl_6 (formerly written as a double salt : $PtCl_4 . 2KCl$) contains no chlorine ions in solution, and gives no precipitate with silver nitrate. According to Werner's theory the chlorine atoms are attached to the platinum atom in the nucleus thus : $[PtCl_6]K_2$, and the ions formed in solution are 2K and $[PtCl_6]''$. The nucleus is indicated in the formula by means of the square brackets.

Although the majority of minerals are insoluble in water and evidence from tests in solution is therefore not available, it is possible that many of the more complex mineral compounds may be of this type, and evidence obtained from the X-ray analysis of certain minerals (*e.g.* spinel) seems to point to such an arrangement of the atoms in the crystal.

times at higher temperatures; sometimes only at red heat. When the water is given off below 100°, as though by evaporation, it is usually regarded as "water of crystallisation," *i.e.* water which is present as such in the mineral. This often appears to be united scarcely, if at all, more tenaciously than the separate molecules in ordinary water, and therefore is not regarded as bound in the ordinary way by bonds or free valencies. Thus many salts, such as mirabilite, $Na_2SO_4 . 10H_2O$, give off their water and break up into powder, or become opaque, if exposed to dry air at ordinary temperatures ("efflorescence").

On the other hand, water which is only given off at high temperatures, approaching a red heat, can scarcely be present in the mineral in the same manner as the water of crystallisation, and it is therefore distinguished as "water of constitution"; this is generally supposed not to exist in the mineral as water, but to result from the union of hydrogen and oxygen, or from hydroxyl, contained in the compound.

Thus, malachite has the empirical formula $Cu_2H_2CO_5$, and since the water is only given off at a high temperature the mineral is regarded as a basic carbonate $(CuOH)_2CO_3$, or as a molecular compound $CuCO_3 . Cu(OH)_2$, in which the water is all water of constitution.

In many hydrated minerals, however, the water is given off in more than two stages. Thus melanterite, $FeSO_4 . 7H_2O$, gives off $3H_2O$ at the ordinary temperature in dry air over sulphuric acid, leaving a residue of $FeSO_4 . 4H_2O$. On heating at 100° C. three more molecules of water are lost, leaving $FeSO_4 . H_2O$. The last water-molecule requires for its expulsion prolonged heating at 250° C.

In such cases it is impossible to draw a simple distinction between water of crystallisation and water of constitution, and a division of this kind becomes arbitrary.

As is well known, a given salt is often capable of crystallising from a solution with several different proportions of water: thus sodium sulphate crystallised from solution at different temperatures yields crystals containing either seven or ten molecules of water; these are totally distinct substances and differ in their crystalline forms and in their densities and other physical characters.

Still another kind of behaviour is observed in the remarkable group of hydrated silicates known as "zeolites." In these minerals the water is not given off at a definite temperature, as in the case of ordinary water of crystallisation, but gradually as the temperature is raised, so that the proportion of water present varies continuously with the temperature. For example, in heulandite, $CaAl_2Si_6O_{16} . 5H_2O$, the water is given off gradually and continuously as the temperature is slowly raised to a red heat. As the dehydration proceeds the optical characters of the mineral change, but if the partly dehydrated specimen be then immersed in water or placed in a moist atmosphere, it will re-absorb the amount lost (provided it has not been raised to too high a temperature), regaining at the same time its original optical and other properties.

The place of the water expelled may also be filled by a number of other substances, such as alcohol, carbon disulphide, hydrogen sulphide, air,

ammonia, or even iodine or mercury. The removal of the water and substitution of other substances here takes place without destroying the crystalline structure of the mineral (see p. 543), and the latter has been compared to a sponge, the water or other substance being held mechanically between the atoms of the anhydrous mineral rather than chemically combined with them.

It will thus be seen that considerable doubt exists as to the part played by the water in any given mineral.

In the formulæ used in this book the water which is given off at a low temperature is expressed as H_2O, written as one of the molecules of a molecular compound; that which is given off at a high temperature is incorporated in the formula as water of constitution.

8. **Complex Acids.**—When an attempt is made to classify minerals according to their acid radicals, a difficulty is encountered in several of the classes because the various minerals in the class cannot all be referred to the same acid. Thus, as shown in the table on p. 230, the silicates cannot all be conveniently referred to the normal acid, $Si(OH)_4$; many silicates, for example, must be referred to an acid $SiO(OH)_2$.

Minerals belonging to the former type are called orthosilicates to distinguish them from those of the latter, which are called metasilicates, and of the two acids the one is tetrabasic and the other is dibasic, containing respectively four and two hydrogen atoms replaceable by metal.

A similar difficulty is met with in other classes, especially among the borates and the sulpho-salts; these classes contain minerals which must be referred to various acids differing in their basicity. Now when the various oxy-acids which must be assumed in any class are compared they are found to differ by multiples of H_2O. Hence these oxy-acids are generally regarded as derived from the normal acid by the removal of a certain number of molecules of water.

Thus, in the case above mentioned, $Si(OH)_4 - H_2O = SiO(OH)_2$.

Among the borates are to be found the following minerals:

Pinnoite, $MgB_2O_4 \cdot 3H_2O$, corresponding to the acid $BO(OH)$.
Borax, $Na_2B_4O_7 \cdot 10H_2O$, ,, ,, $B_4O_5(OH)_2$.
Colemanite, $Ca_2B_6O_{11} \cdot 5H_2O$, ,, ,, $B_6O_7(OH)_4$.

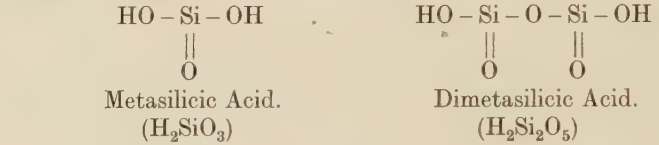
Here (omitting the water of crystallisation) the acid of borax may be derived from that of pinnoite by removing one molecule of water from four of the latter, thus: $4HBO_2 - H_2O = H_2B_4O_7$; the acid of colemanite by removing one molecule of water from six of the same: $6HBO_2 - H_2O = H_4B_6O_{11}$.

Among the silicates the following acids, derived in the same manner from orthosilicic acid, $Si(OH)_4$, are sometimes assumed in order to express the constitution of the many and important minerals included in the class of silicates.

$H_4SiO_4 = Si(OH)_4$ . . . . . Orthosilicic acid.
$H_6Si_2O_7 = 2Si(OH)_4 - H_2O$ . . . Diorthosilicic acid.
$H_8Si_3O_{10} = 3Si(OH)_4 - 2H_2O$ . . . Triorthosilicic acid.

$H_2SiO_3 = Si(OH)_4 - H_2O$ . . . Metasilicic acid.
$H_4Si_3O_8 = 3Si(OH)_4 - 4H_2O$ . . . Trimetasilicic acid.
$H_2Si_2O_5 = 2Si(OH)_4 - 3H_2O$ . . . Dimetasilicic acid.

Such acids may be represented as having the following type of constitution :



Metasilicic Acid. (H_2SiO_3) Dimetasilicic Acid. ($H_2Si_2O_5$)

There is unfortunately no direct evidence of the existence of most of these acids, as the silicates are very stable and insoluble substances, which cannot be vaporised or obtained in solution without decomposition ; but in the case of some few silicic acids organic esters, whose molecular weights are known, have been prepared. Such are the esters : Et_2SiO_3, Et_4SiO_4, $Et_2Si_2O_5$ and $Et_6Si_2O_7$, corresponding to metasilicic, orthosilicic, dimetasilicic and diorthosilicic acid.

In this and other complicated classes, however, it is not really possible to say with certainty to what acid a given mineral is to be referred. Thus a mineral of the composition Al_2SiO_5 might either be a normal salt of an acid H_6SiO_5, or have the constitution $(AlO)'_2SiO_3$ (*i.e.* a basic salt of metasilicic acid) or $Al(AlO)'SiO_4$ (*i.e.* a partly basic salt of orthosilicic acid). There is no evidence, however, for the existence of an acid H_6SiO_5, and the mineral cyanite may probably correspond to the metasilicate formula $(AlO)'_2SiO_3$, while another mineral of the same empirical composition, andalusite, may probably be the basic orthosilicate $Al(AlO)'SiO_4$.

Amongst the class of sulpho-salts (sulpharsenites, sulphantimonites, sulphobismuthites) also the existence of a large number of hypothetical acids has been assumed, derived from the normal acid $As(SH)_3$ by removal or addition [1] of different numbers of groups H_2S.

A few of these, which correspond to well-known minerals, are the following :

$HAsS_2 = As(SH)_3 - H_2S$ . . *e.g.* Scleroclase, $PbS . As_2S_3$. (Metasulpharsenites.)
$H_4As_2S_5 = 2As(SH)_3 - H_2S$ . . *e.g.* Dufrenoysite, $2PbS . As_2S_3$.
$H_3AsS_3 = As(SH)_3$ . . . *e.g.* Proustite, $3Ag_2S . As_2S_3$. (Orthosulpharsenites.)
$H_8As_2S_7 = 2As(SH)_3 + H_2S$ . . *e.g.* Jordanite, $4PbS . As_2S_3$.
$H_5AsS_4 = As(SH)_3 + H_2S$ . . *e.g.* Stephanite, $5Ag_2S . Sb_2S_3$.

In view of the complicated and entirely hypothetical nature of these acids, the formulæ of the corresponding minerals are frequently written simply in the form $mR'_2S . nAs_2S_3$, where R'_2 represents two atoms of a monovalent (or one atom of a divalent) metal, as shown in the last column of the table.

[1] The constitution of compounds of the latter kind, containing an excess of H_2S, cannot be expressed by ordinary valency formulæ, and it is probable that many of the sulpho-salts are complex co-ordination compounds as represented by A. Werner. Experimental evidence, however, is wanting, as the compounds are all insoluble.

9. **Classification of the Silicates.**—The preceding remarks will have made it clear that in regard to minerals very little experimental evidence is yet available which can throw any light upon their constitution. The percentage composition having been ascertained by quantitative analysis, little at present can be done towards establishing constitutional formulæ, except to compare minerals with any of the more tractable compounds which can be made or experimented upon in the laboratory, especially such as are volatile and soluble, and to which they may be in some way allied. Mineralogy is to a large extent the chemistry of silicon compounds —about half the minerals known are silicates—but unfortunately it has not yet proved possible to apply to these any of the methods which have been so fruitful in the study of the carbon compounds in organic chemistry ; their constituents cannot be replaced by organic radicals, nor can series of derivatives be prepared ; their vapour density cannot be determined, nor their physical behaviour in solution. We have to content ourselves with the analogies which they may present with other compounds which are better understood, and the relations which they bear to each other.

In a descriptive science like mineralogy mutual relations may well be brought to light by testing various schemes of classification, just as in zoology or botany the essential relationships between various animals or various plants have been gradually discovered by testing different systems of classification until the most satisfactory arrangement into species and genera has been evolved.

It has already been stated that the main grouping of minerals is into such classes as carbonates, phosphates, and silicates, by means of the non-metallic radicals which, in accordance with the general principles of experimental chemistry, they are supposed to contain ; and that on account of the similarity and equivalence of their elements the class of phosphates, for example, is coupled with arsenates and vanadates, and the class of silicates with titanates and zirconates.

The difficulties which are as yet experienced in subdividing satisfactorily within these large groups on any chemical principle alone may be illustrated by mentioning some of the methods which have been in common use in classifying the important but difficult class of silicates.

(1) *By the Oxygen Ratio.*—This classification simply depends upon the atomic ratio of the oxygen contained in the silica to that in the bases.

Whatever may be the type of acid to which a silicate is referable, the nature of a salt renders it clear that any silicate can be expressed as a compound of certain metallic oxides or bases with a certain amount of silica. Thus an orthosilicate R''_2SiO_4 is expressible as $2R''O \cdot SiO_2$, in which the base contains two atoms of oxygen and the silica contains also two atoms of oxygen ; the oxygen ratio is therefore 1 : 1, and such compounds may be called unisilicates.

A metasilicate $R''SiO_3$ or $R''O \cdot SiO_2$ has the oxygen ratio 2 : 1, and may be called a bisilicate.

Many important minerals are trisilicates of the type $R''_2Si_3O_8$ or $2R''O \cdot 3SiO_2$, in which the ratio is 3 : 1.

Those minerals in which the oxygen ratio is 3 or more are sometimes

classed together as polysilicates; and those in which the oxygen ratio is less than 1 are called subsilicates.

An arrangement of this difficult class of minerals in order of the oxygen ratios has the advantage of avoiding to a great extent any theoretical views as to the structure of the silicate or any prejudice regarding the acid of which it is a salt.

It is probable, however, that certain weak bases, such as alumina and ferric oxide, may in some cases belong to the acid instead of to the basic part of the silicate, and there is no certain ground for referring them to the one rather than the other side of the oxygen ratio.

That the oxygen ratio may fail to indicate true relationships may be seen from the following three minerals, of which the empirical formulæ are perfectly well established: lime-garnet, albite, and anorthite.

Lime-garnet.	%	Albite.	%	Anorthite.	%
CaO	37·4	Na_2O	11·8	CaO	20·2
Al_2O_3	22·6	Al_2O_3	19·4	Al_2O_3	36·6
SiO_2	40·0	SiO_2	68·8	SiO_2	43·2

From these percentages the empirical formulæ are—

Lime-garnet	$3CaO . Al_2O_3 . 3SiO_2$	or $Ca_3Al_2Si_3O_{12}$.
Albite	$Na_2O . Al_2O_3 . 6SiO_2$	or $NaAlSi_3O_8$.
Anorthite	$CaO . Al_2O_3 . 2SiO_2$	or $CaAl_2Si_2O_8$.

According to their oxygen ratio, therefore—

Lime-garnet is a unisilicate; ratio 1 : 1,
Albite ,, trisilicate; ratio 3 : 1,
Anorthite ,, unisilicate; ratio 1 : 1.

In reality, however, nothing can be more certain than that albite and anorthite are very closely related by all their properties, while garnet is a mineral quite distinct from them.

(2) *As Salts of various Silicic Acids.*—Many of the natural silicates may be represented as normal salts of the following possible silicic acids:

H_4SiO_4,	yielding orthosilicates;	*e.g.* olivine, Mg_2SiO_4.
H_2SiO_3,	,, metasilicates;	*e.g.* enstatite, $MgSiO_3$.
$H_6Si_2O_7$,	,, diorthosilicates;	*e.g.* barysilite, $Pb_3Si_2O_7$.
$H_2Si_2O_5$,	,, dimetasilicates;	*e.g.* titanite, $CaSiTiO_5$.

The majority of the known silicates which occur in nature can be referred to one or other of these acids as normal, acid or basic salts, either hydrated or anhydrous, or as molecular compounds.

If the three minerals mentioned above are to be referred to these four acids—

Lime-garnet would be regarded as a normal orthosilicate, $Ca_3Al_2(SiO_4)_3$,
Albite as a normal salt (metasilicate and di-metasilicate), $NaAl(SiO_3)(Si_2O_5)$,
Anorthite as a normal orthosilicate, $CaAl_2(SiO_4)_2$.

But here again the close relationship which undoubtedly exists between albite and anorthite finds no expression. If one is to regard them as similar salts, the atoms SiNa of albite must be replaced by the atoms AlCa of anorthite, so that, as suggested above, part of the Al of anorthite belongs to the acid portion of the formula.

(3) *As Substitution Derivatives of Normal Aluminium Silicates.*—Most of the natural silicates are compounds containing aluminium, and F. W. Clarke has endeavoured to express all the minerals of this class as substitution derivatives of such compounds as the normal aluminium orthosilicate $Al_4(SiO_4)_3$, in which one or more of the aluminium atoms can be replaced by trivalent radicals, or by groups of divalent or monovalent radicals.

According to this view—

Lime-garnet is $Al_2Ca_3(SiO_4)_3$,
Anorthite is $Al_6Ca_3(SiO_4)_6$.

Both are orthosilicates, and the latter is derived from $2Al_4(SiO_4)_3$ by replacing Al_2 by Ca_3.

Albite is $Al_3Na_3(Si_3O_8)_3$,

and is to be regarded as derived from another normal salt whose formula is $Al_4(Si_3O_8)_3$, so that even here a second acid must be introduced into the scheme.

For, clearly, if albite and anorthite are to have any close chemical relationship the acids H_4SiO_4 and $H_4Si_3O_8$ must be regarded as analogous, and therefore the acid radical SiO_4 as replaceable by and equivalent to the acid radical Si_3O_8.

In all these instances, without proceeding so far as to assign graphic formulæ, an attempt is made to show how the atoms can be grouped into mutually replaceable radicals in a manner consistent with the nature of the whole class of silicates.

It will now, however, be clear from the examples given that all such attempts are of a highly speculative nature; and although by means of the X-ray analysis of crystallised minerals much light has recently been thrown on the arrangement of the atoms in the crystal and the number of atoms which are contained in the unit particles of which the crystal is built up (see Book IV, Chapter II), little is known at present as to the way in which these atoms are connected together to form molecules, as in the structural formulæ of organic chemistry.

It is also clear that minerals such as albite and anorthite are classed together, not solely, or indeed at all, on account of their chemical similarity, but because, by reason of their other properties, they are first known to be closely related; an effort is then made, by manipulating the empirical formulæ, to express the relationship by means of the mutual replacement of equivalent radicals.

To this extent, then, the natural history methods of Werner and

Mohs, mentioned at the beginning of this chapter, were completely justified; these mineralogists never had any hesitation in classifying together albite and anorthite under one mineral group—felspar—because by all their external characters they are clearly very intimately related to one another; it was therefore fortunate that in the order of events a natural history classification should have preceded a more chemical system, and that mineralogists became more or less agreed as to the minerals which belonged to the same group before attempting to explain why they were to be classed together.

The modern classification of minerals, though apparently chemical, is by no means purely so, and we are at once driven to the subject of the next book—the relationship between the chemical composition and the physical properties.

Further, it must be remembered that up to the present our attention has been confined to those minerals whose analyses lead to simple atomic proportions for the elements which they contain. In reality, however, most mineral analyses lead to proportions which are not in the ratio of simple numbers of atoms of one element to those of another, as in the case of the analyses quoted above.

This and the preceding difficulties can only be overcome with the help of the great principles of isomorphism and of the mixture of crystallised solids which we proceed to consider in Book III.

If the present chapter appears to have merely indicated how little is known of the composition of even the simpler minerals beyond their empirical formulæ, the next chapter will show how much has been discovered which at any rate expresses the composition of the more complicated minerals in terms of the simpler.

BOOK III

THE RELATIONS BETWEEN THE CHEMICAL COMPOSITION AND THE PROPERTIES OF MINERALS

THE RELATIONS BETWEEN THE CHEMICAL COMPOSITION AND THE PROPERTIES OF MINERALS

1. **Isomorphism, Polymorphism, and Vicarious Replacement.**—One of the main results of Haüy's work was to establish the principle that every substance has its own characteristic crystalline form, and that (except in the cubic system) the crystals of different substances are different in angles; and although Haüy was aware that some substances, particularly barytes, $BaSO_4$, and celestine, $SrSO_4$, which resembled one another in composition, were nearly related also in crystalline form, it was not until the researches of Mitscherlich in 1819, upon the phosphates and arsenates of potassium and ammonium, that the existence of a relation between the form of a crystal and its composition was conclusively proved. Mitscherlich showed, for instance, that the acid phosphate of potassium, KH_2PO_4, possesses what is apparently the same crystalline form as the acid arsenate of potassium, KH_2AsO_4, and these two substances are clearly also similar in their chemical composition.

Two substances which have a similar composition and the same (or nearly the same) crystalline form were called "isomorphous."

Among minerals, the rhombohedral carbonates:

Calcite	$CaCO_3$
Magnesite . . .	$MgCO_3$
Chalybite . . .	$FeCO_3$
Calamine . . .	$ZnCO_3$
Rhodochrosite . .	$MnCO_3$

were regarded as typical isomorphous compounds.

Further, Mitscherlich subsequently showed (1821) that an element or compound may occur in two (or more) distinct forms. Sulphur, for example, exists both in orthorhombic and in several sorts of monoclinic crystals.

A substance which can crystallise in two or more distinct forms was called "dimorphous" or "polymorphous."

Among minerals,

Calcite . . .	$CaCO_3$—Hexagonal
Aragonite . . .	$CaCO_3$—Orthorhombic

afford a typical instance of a dimorphous compound;

Anatase	.	TiO_2—Tetragonal
Rutile	.	TiO_2—Tetragonal, with axes different from those of anatase,
Brookite	.	TiO_2—Orthorhombic

form an example of a trimorphous compound.

A very important suggestion had been made a short time previously by Fuchs, who pointed out that in the mineral gehlenite, although it is essentially a silicate of lime and alumina ($3CaO . Al_2O_3 . 2SiO_2$), a certain proportion of oxide of iron is present, and that this may be regarded as replacing a certain proportion of the lime; if, therefore, the composition of the mineral is to be expressed by simple numbers, the *sum* of these two constituents, and not their individual proportions, must be taken into account. "I believe," he says, "that, in the future, varieties will be found which contain less or even no oxide of iron, but a larger quantity of lime."

The constituents which can thus replace one another in a compound were called "vicarious" constituents.

Among minerals the garnet group offers a typical example of vicarious constituents. In the following garnets:

Grossular	$3CaO . Al_2O_3 . 3SiO_2$
Pyrope	$3MgO . Al_2O_3 . 3SiO_2$
Almandine . . .	$3FeO . Al_2O_3 . 3SiO_2$
Andradite	$3CaO . Fe_2O_3 . 3SiO_2$
Uvarovite	$3CaO . Cr_2O_3 . 3SiO_2$

the oxides CaO, MgO, FeO are one set of vicarious constituents, and the sesquioxides Al_2O_3, Fe_2O_3, Cr_2O_3 are another set; and in most specimens of garnet several of these vicarious constituents are present replacing one another to a greater or less extent.

Upon these three facts:

(1) Similar compounds have nearly the same form (isomorphism),
(2) A compound may crystallise in several forms (polymorphism),
(3) Similar atoms or radicals may partially replace each other without altering the form (isomorphous mixture),

rests the whole structure of modern mineralogical classification, and it is only by their aid that order has been introduced into systematic mineralogy; minerals were previously classified either by their form or their composition, and the two classifications did not lead to the same result.

The following remark of Fuchs, relating to the alums, is an early indication of the feeling that substances closely related in other respects must possess also a close chemical relationship.

"Sulphate of alumina forms, with ammonium, an alum just as well as with potash or with both these alkalies. Is it convenient to treat as three separate salts these three compounds, which do not differ at all in their physical properties? The potash can here be completely or partially replaced by ammonium, and *vice versa*."

In accordance with this principle, minerals of apparently diverse composition, such as almandine and uvarovite, or potash-alum and ammonia-

alum, could now be classified together if they possessed the same, or nearly the same, crystalline form, and contained vicarious elements, even though they might have not a single constituent in common. The new views received immediate and rapid support from chemical analyses, which showed that many minerals of the same form are also similar in composition.

Mitscherlich had at first assumed that the crystalline forms of substances like potassium phosphate and potassium arsenate, whose crystals resembled one another, were identical. Now the doctrine that two substances of different composition could crystallise in the same form, and further, that a single substance having a definite composition could crystallise in more than one form, appeared to destroy all that was exact in the science of mineralogy, which Haüy had so successfully erected upon a crystallographical basis, and the new views were strongly opposed by Haüy, who considered the crystalline form to be a more certain indication of identity or otherwise than the results of analysis, owing to the frequent presence of impurities in the material analysed.

Thus in the neighbourhood of Paris were found rough crystals (known as "Fontainebleau sandstone") having the form of calcite, which, on analysis, proved to consist of sand grains up to the extent of 60 per cent or more. Here the crystalline form was due, not to the sand, but to the much smaller quantity of calcite which the crystals contain. The calcite, it was urged, possesses so powerful a crystallising action that it can impress its own characteristic form upon the sand.

Similarly, crystals of dolomite, chalybite, and magnesite were considered by Haüy to have the same form as calcite, not by reason of their own composition, but on account of a proportion of calcium carbonate which they contain.

More accurate measurements showed, however, that two isomorphous substances have not in reality precisely the same form, as was at first supposed; on the contrary (except in the cubic system), the angles of two isomorphous substances are probably never precisely identical.

Thus such substances do not really form an exception to Haüy' generalisation, and eventually the principle of isomorphism and of the mutual replacement of vicarious constituents became firmly established.

2. **Mineral Groups.**—Bearing the above principles in mind we may now see how they enable us to bring together by *chemical* relationships minerals which, on account of their similarity of form and physical properties, constitute a natural group, and which would have been brought together in any case under the Natural History System without regard to their composition.

The anhydrous carbonates of the elements calcium, magnesium, iron, zinc, and manganese all crystallise in the rhombohedral system, and their crystals have *nearly* the same angles; thus,

Calcite	$CaCO_3$	Rhombohedron-angle	74°	55′
Magnesite	$MgCO_3$	,, ,,	72°	36′
Chalybite	$FeCO_3$	,, ,,	73°	0′
Calamine	$ZnCO_3$	,, ,,	72°	20′
Rhodochrosite	$MnCO_3$	,, ,,	73°	0′

Further, they all have a perfect cleavage parallel to the faces of this rhombohedron.

In a "mineral group" such as this, which consists of similar compounds crystallising in nearly identical rhombohedra, it is evident that whatever the relation between the crystalline form and chemical composition may be, it must be the same for each member of the group.

In the above group, which is known as that of the "rhombohedral carbonates," the similarity of composition consists in the fact that all the minerals have the same acid radical and only differ in the metal with which it is combined; and further, that these metals possess the same valency.

In some mineral groups the crystalline forms of the contained metals are also similar to one another.

The following group, for example, is one in which the metallic elements themselves have similar forms, or are isomorphous:

Orpiment . .	As_2S_3	Orthorhombic	$a : b : c = 0{\cdot}924 : 1 : 1{\cdot}052$
Stibnite . .	Sb_2S_3	,,	,, $= 0{\cdot}993 : 1 : 1{\cdot}018$
Bismuthite . .	Bi_2S_3	,,	,, $= 0{\cdot}968 : 1 : 0{\cdot}985$,

for the metals arsenic, antimony, and bismuth all crystallise in the rhombohedral system and have nearly the same angles:

Arsenic . . .	Rhombohedron-angle 94° 54′
Antimony . . .	,, ,, 92° 53′
Bismuth . . .	,, ,, 92° 20′

In this group of sulphides, therefore, the similarity of composition consists in the fact that the minerals contain the same element, sulphur, combined with the same number of atoms of equivalent metals which are themselves isomorphous with each other.

Or, in the language of Fuchs, the relation may be expressed in another way. In a mineral group one element (or radical) is capable of replacing, partially or entirely, another element (or radical) without introducing any considerable change in the crystalline form. The elements or radicals which are capable of this mutual replacement are often called isomorphous even when nothing is known of their own crystalline form.

That this replacement may take place either among the bases or in the acid radicals is apparent from the following instances:

Celestite, $SrSO_4$ . .	Orthorhombic	$a : b : c = 0{\cdot}7789 : 1 : 1{\cdot}2800$
Barytes, $BaSO_4$ . .	,,	,, $= 0{\cdot}8152 : 1 : 1{\cdot}3136$
Anglesite, $PbSO_4$ . .	,,	,, $= 0{\cdot}7852 : 1 : 1{\cdot}2894$
Scheelite, $CaWO_4$	Tetragonal	$a : c = 1 : 1{\cdot}537$
Stolzite, $PbWO_4$	,,	,, $= 1 : 1{\cdot}567$
Wulfenite, $PbMoO_4$ . . .	,,	,, $= 1 : 1{\cdot}574$
Erythrite, $Co_3(AsO_4)_2 . 8H_2O$	Monoclinic	$a : b : c = 0{\cdot}7937 : 1 : 0{\cdot}7356$, $\beta = 74° 51′$
Vivianite, $Fe_3(PO_4)_2 . 8H_2O$	,,	,, $= 0{\cdot}7489 : 1 : 0{\cdot}7017$, $\beta = 75° 34′$

A comparison of wulfenite with scheelite, or of vivianite with erythrite, shows that the replacement may take place simultaneously in the basic and the acid radical.

In a mineral group there is always some difference in the form, that is to say in the angles, of the various members of the series, except when these belong to the cubic system; in the latter case they must be absolutely identical in form, since the corresponding forms of all cubic crystals have the same angles whatever their composition; as an example of a mineral group in the cubic system we have salt, NaCl, and sylvite, KCl, cerargyrite, AgCl, and bromargyrite, AgBr.

In some cases it appears that two univalent atoms or radicals may replace one divalent atom or radical; three divalent atoms may replace two trivalent atoms, and so on. Thus chrysoberyl, $BeAl_2O_4$, and diaspore, $H_2Al_2O_4$, show a certain resemblance to one another in crystalline form; and similarly phenakite, Be_2SiO_4, and dioptase, H_2CuSiO_4. In the first instance, two univalent atoms of hydrogen replace one divalent atom of beryllium; in the second instance, the tetravalent group Be_2 is replaced by the tetravalent group H_2Cu. In reality the relation between such compounds is not usually very close, nor do they usually form isomorphous mixtures.

In some of the more complex silicates, however, isomorphous replacement of this kind does occur, as in the pyroxene group, in which silicates of univalent and trivalent metals, such as spodumene, $LiAl(SiO_3)_2$, are isomorphous with those of divalent metals, such as diopside, $CaMg(SiO_3)_2$. A still wider range of replacement occurs in highly complex minerals like tourmaline, the composition of which may be expressed (according to Penfield) by the formula $R'_9Al_3(BOH)_2Si_4O_{19}$, where R′ represents H, Na, Li, or equivalent amounts of Mg, Fe, Al, replacing one another in varying proportions. Here the form remains constant in spite of the replacement of dissimilar atoms, owing to the preponderating effect of the aluminium-boro-silicate-portion of the molecule.

The chief groups of vicarious elements and radicals among minerals are—

K, Rb, Cs. Na, Li, NH_4, in the haloids, phosphates, and silicates.
F, Cl, Br, I, OH, in the haloids, phosphates, and silicates.
Cu′, Ag, Au, Hg, Tl, Pb, in the sulphides and sulpho-salts.
Be, Mg, Ca, Mn″, Fe″, Zn, Cu″, in the phosphates and silicates.
Mg, Mn″, Fe″, Co″, Ni″, Zn, Cu″, in the sulphates.
Ca, Sr, Ba, Pb, in the carbonates and sulphates.
Mg, Ca, Zn, Fe″, Mn″, in the carbonates.
Fe″, Co″, Ni″, Mn″, Zn, Cd, in the sulphides and arsenides.
Al, Fe‴, Cr‴, Mn‴, in the oxides, aluminates, phosphates, and silicates.
Y, Er, Ce, La, Di, in the haloids, phosphates, silicates, etc.
S, Se, Te, in the sulphides, selenides, and tellurides.
As, Sb, Bi, in the oxides, sulphides, and sulpho-salts.
Si, Ti, Zr, in the silicates, titanates, and zirconates.
P, V, As, in the phosphates, vanadates, and arsenates.
Mo, W, in the molybdates and tungstates.
Nb, Ta, in the niobates and tantalates.

3. **The Physical Relations of Minerals belonging to the same Group.**—Isomorphous minerals really differ in their physical properties as well as in their form and composition. Even when an isomorphous group belongs to the cubic system, so that its members cannot be distinguished by their angles, they possess different physical characters according to their composition. Thus common alum, $KAl(SO_4)_2 . 12H_2O$, and chrome-alum, $KCr(SO_4)_2 . 12H_2O$, differ in their general characters such as specific gravity:

	Spec. Grav.
Common alum	1·735
Chrome-alum	1·817

They can also be distinguished by their crystallophysical characters, both those which in the cubic system differ for different directions, *e.g.* the elasticity, and those which, like the refractive index or the thermal conductivity, are the same for all directions.

In the matter of elasticity, if P denote the weight in kilograms theoretically sufficient to extend a rod whose section is a square millimetre cut out of a crystal parallel to a cube-edge, to double its length, and if Q denote the weight required for a rod of similar section cut parallel to a cube-diagonal, we have—

	P	Q	Refractive Index
Common alum	1806	2058	1·4557
Chrome-alum	1608	1832	1·481

Thus if account be taken of *all* their properties, there is no risk of confusing different substances which resemble one another in angles, even in the cubic system.

When the isomorphous substances belong to some other system they differ, of course, still more conspicuously in physical characters, since their double refraction is not the same.

The principal refractive indices may differ not only in their absolute magnitudes, but also in their ratios, and where it is possible (in the monoclinic and anorthic systems) the axes of the indicatrix may occupy different positions.

Thus, of the tetragonal dithionates, $CaS_2O_6 . 4H_2O$, $SrS_2O_6 . 4H_2O$, and $PbS_2O_6 . 4H_2O$, the first two are negative and the third is positive.

Again, in all the members of the orthorhombic aragonite group the acute bisectrix is perpendicular to the basal plane (001) and the birefringence is negative, but the axial plane is parallel to the macro-pinakoid (100) in aragonite, $CaCO_3$, and strontianite, $SrCO_3$, but to the brachy-pinakoid (010) in witherite, $BaCO_3$, and cerussite, $PbCO_3$.

In the group of monoclinic pyroxenes the plane of the optic axes is always the clino-pinakoid (010), but the extinction-angle on this face, *i.e.* the inclination of the acute bisectrix to the vertical axis, varies as follows:

Acmite	$NaFe(SiO_3)_2$	$5\frac{1}{2}°$ $(=c\alpha)$
Spodumene	$LiAl(SiO_3)_2$	$26°$ $(=c\gamma)$
Diopside	$CaMg(SiO_3)_2$	$38°$ $(=c\gamma)$
Hedenbergite	$CaFe(SiO_3)_2$	$47°$ $(=c\gamma)$

On the other hand, there are numerous instances in which the optical characters of the members of an isomorphous group, though different, are closely related. In the barytes group, for example, all three minerals are positive, have the acute bisectrix perpendicular to (100), and have the plane of the optic axes parallel to (010).

Generally speaking, the cleavages are parallel to the same forms in all the members of an isomorphous group ; but they may differ in facility. Thus anglesite, $PbSO_4$, possesses the same cleavages—prism {110} and basal pinakoid {001}—as barytes, $BaSO_4$, and celestite, $SrSO_4$; but they are by no means so perfect in anglesite as in the other two minerals.

Again, with polymorphous substances, the several forms differ, not only in their angles, and in the crystallophysical characters which might naturally be expected to depend on the crystalline form, but also in their general physical characters. Iron pyrites and marcasite have the same empirical formula, FeS_2, but the two minerals differ in specific heat and specific gravity as well as in their crystalline form :

		Spec. Grav.	Spec. Heat
Iron pyrites .	Cubic . .	5·03	0·1306
Marcasite .	Orthorhombic .	4·88	0·1332

It may happen that two isomorphous compounds, or the two forms of a dimorphous compound, appear to be identical in some one physical property, at least so far as present experimental methods are able to determine it, but they cannot be identical in all their physical properties.

Thus, chalybite, $FeCO_3$, and rhodochrosite, $MnCO_3$, both have a rhombohedron angle of 73° 0′, but their specific gravity is different (chalybite, 3·86 ; rhodochrosite, 3·52).

Calcite ($CaCO_3$ –rhombohedral) and aragonite ($CaCO_3$—orthorhombic) have nearly the same specific heat, 0·2036, but they differ markedly in specific gravity (calcite, 2·713 ; aragonite, 2·93).

The two common modifications of sulphur have nearly the same specific gravity, but differ in their specific heat, that of the monoclinic variety being higher than that of orthorhombic sulphur.

The fact that two substances may consist of the same elements combined in the same proportions but yet have different properties, may be due either to a different arrangement of the atoms within the molecule (chemical isomerism), or to the fact that the molecules, though similar, are differently arranged to form the crystal. In the latter case the difference between the substances can only exist in the crystalline state and will disappear on fusion or solution in a solvent, and the liquids obtained from both substances will be identical in their properties. It is to this case that the name polymorphism should strictly be confined. In the former case the properties of the two substances will be different in the liquid and gaseous states as well as in crystals.

Among organic compounds it may often be possible by means of the vapour-density and the study of the chemical reactions to distinguish between the two cases, but among minerals experimental evidence is at present wanting, and any distinction of the kind is merely hypothetical,

so that in mineralogy the term *polymorphous* is commonly applied in all cases where two or more minerals have the same composition but different crystalline forms.

A particular form of a polymorphous substance is usually found to be stable only within certain limits of temperature, outside of which it becomes unstable and tends to be converted, more or less rapidly, into another form. Thus sulphur, when allowed to crystallise from the molten state, at a temperature of 119°, forms prisms belonging to the monoclinic system. But these, if cooled below 95°, are gradually converted into an aggregate of crystals of orthorhombic sulphur, the variety which is stable at the ordinary temperature, and which is obtained if a solution of sulphur in carbon disulphide or chloroform is allowed to crystallise spontaneously. This transformation of one form of a substance into another on change of temperature is very commonly observed in substances prepared in the laboratory, and is also exhibited by certain minerals, such as leucite and boracite.

It may be supposed that the physical properties of a compound might be deducible from those of its constituents if we had a complete knowledge of the nature of these constituents and of the way in which they are united and arranged. At present, however, though by means of X-rays the mode of arrangement of the constituent atoms in a crystal can now in many cases be determined, we are still far from being able to predict either the crystalline form or the properties of a mineral from a knowledge of its constituent elements.

The case is different, however, if we confine our attention to a set of minerals in which there is reason to believe that the constituent atoms are related to each other in precisely the same way in the various members of the group.

This is certainly the case in a series of isomorphous compounds, in which the influence of the different vicarious constituents may be directly compared. Here, without knowing what is the exact relation between the properties of the compound and those of its constituents, we may confidently assert that the relation is the same for all the members of the series, and in some cases may even predict the properties of some as yet unknown compound belonging to it.

For example, potassium, rubidium, and cæsium are three monovalent elements occupying corresponding positions in the even series of the periodic table (p. 226), and they act as vicarious constituents in a number of isomorphous salts.

The atomic weight of rubidium lies between those of potassium and cæsium. Tutton has compared numerous compounds of these metals, for example the simple sulphates, K_2SO_4, Rb_2SO_4, and Cs_2SO_4, and has shown that as regards crystalline form, specific gravity, thermal expansion, and corresponding refractive indices, the rubidium salt lies between the potassium and cæsium salts.

The same is true of the rubidium compound, as compared with the potassium and cæsium compounds, in more than fifty double sulphates, selenates, and chromates, studied by the same observer and belonging to

the series whose formula is $R'_2SO_4 . R''SO_4 . 6H_2O$, where R′ may be K, Rb, or Cs; R″ may be Mg, Zn, Fe, Ni, Co, Cu, Mn, or Cd; and S may be replaced by Se or Cr. For each triad of salts in which R″ is the same divalent metal, the properties of the rubidium salt are intermediate between those of the potassium and the cæsium salts.

There can be little doubt that in an isomorphous series of closely related or "eutropic" compounds such as this, the properties of the salts are similar functions of the atomic weights of the elements. It is certain also that the properties of the elements themselves are periodic functions of their atomic weights, and therefore that in an isomorphous series the properties of each member are related in one and the same way to the properties of its constituents. Thus the K-Mn compound and the K-Cd compound belonging to the above series of double sulphates have not yet been prepared, but their crystalline form, specific gravity, and refractive indices can be predicted on the assumption that K, Mn, and Cd will play the same part in them as in the known compounds.

Among minerals, few series are known which are so closely related as the above. The members of a mineral group are often corresponding compounds of elements which are somewhat closely related, but not so closely as are K, Rb, and Cs.

Nevertheless, a large number of minerals do naturally fall into groups like the calcite group, in which similarity of crystalline form is evidently accompanied by similarity of composition, and also by similarity of physical properties, in the sense that as one constituent is replaced by another, corresponding changes are introduced into the physical properties.

In these, however, it cannot be said that all the corresponding numbers follow in general the same order as the atomic weights of the vicarious constituents. In the aragonite group we have—

	$a : b : c$	Sp. Gr.	Refr. Index	Sp. Heat
Aragonite, $CaCO_3$ (Ca = 40)	0·6228 : 1 : 0·7207	2·95	$\gamma = 1·6859$	0·2036
Strontianite, $SrCO_3$ (Sr = 87)	0·6089 : 1 : 0·7237	3·70	$\gamma = 1·6670$	0·1445
Witherite, $BaCO_3$ (Ba = 137)	0·5949 : 1 : 0·7413	4·30	$\beta = 1·6760$	0·1096
Cerussite, $PbCO_3$ (Pb = 207)	0·6220 : 1 : 0·7168	6·50	$\beta = 2·0763$	0·1086

Neither in the aragonite group nor in the barytes group quoted above do the axial ratios follow in the order of the atomic weights of the vicarious constituents, except so far as the eutropic elements Ca, Sr, Ba are concerned. The element Pb introduces a sudden change in the series; its compounds are isomorphous, but not eutropic, with those of Ca, Sr, Ba.

The refractive indices which are compared in the above table are those which belong in each case to the axis b; in aragonite and strontianite this axis is the obtuse bisectrix (γ), in the other two minerals it is the perpendicular to the plane of the optic axes (β).

It will be seen, however, that their values do not follow the order of the atomic weights even in the case of the Ca, Sr, Ba compounds.

Thus a mineral group may exhibit similarity of form, composition, and other properties without possessing a regular sequence of properties

in the order of the atomic weights of the replacing elements; or, in other words, a mineral group may be isomorphous without being a "eutropic" series.

Sometimes the change produced by such replacement is so great that the two compounds can scarcely be called isomorphous in the strict sense. They may not only differ considerably in angles but even in symmetry; they may belong to different classes within the same system, or they may even belong to different systems, while preserving an obvious similarity in angles.

Thus calcite, $CaCO_3$, possesses an axis of alternating *di-hexagonal* symmetry; dolomite, $CaCO_3 . MgCO_3$, crystallises in almost the same rhombohedra and has the same cleavage, but though its angles are so close to those of calcite, its symmetry is different, and it possesses an axis of alternating *hexagonal* symmetry. It is true that dolomite may differ chemically from calcite in being a double salt. But the close relationship between the two minerals, both in physical and chemical properties, compels us to refer dolomite without any hesitation to the calcite group.

Again, albite, $NaAlSi_3O_8$, and orthoclase, $KAlSi_3O_8$, must be referred together to the felspar group on account of their intimate relations, in spite of the fact that albite is anorthic, and orthoclase to all appearance monoclinic.

Some authors wish to reserve the term "isomorphous" exclusively for those compounds in which the relationships are absolutely uniform, as in the sulphates of potassium, rubidium, and cæsium.

Hence the term "mineral group" is used in this book for what are sometimes called "isomorphous" groups, and it must be understood to mean a group of minerals which possess a close similarity in crystalline form and cleavage, and usually resemble one another more or less closely in chemical composition, whether their symmetry be the same or not. In certain groups, such as that of the felspars, though the form and cleavage are very similar, chemical similarity is less obvious, but close relationship is proved by the occurrence of homogeneous mixtures (*cf.* pp. 263, 512).

A similarity in crystalline form may sometimes be traced in minerals whose constituent elements are not closely—or even at all—related, but which have a similar type of composition.

Thus the two minerals, zincite, ZnO, and greenockite, CdS, belong to the distinct chemical groups of oxides and sulphides, and can scarcely be called isomorphous. But their composition is similar in the sense that oxygen is replaced by sulphur and cadmium by zinc, and in form they are almost identical, since zincite belongs to the greenockite class of crystals and has almost the same angles as greenockite. Moreover, the arrangement of the atoms in the crystals is the same in both, as well as in wurtzite, ZnS, which is isomorphous with greenockite and forms a connecting link between zincite and greenockite (*cf.* pp. 370, 401).

Such relations are by no means rare. Other oxides are found to be very similar in form to the corresponding sulphides; for example, the

orthorhombic oxide valentinite, Sb_2O_3, to the orthorhombic sulphide stibnite, Sb_2S_3.

Another remarkable instance of this is afforded by calcite and sodium nitrate, which both crystallise in the same class of the hexagonal system, with very nearly the same angles, and both show a perfect rhombohedral cleavage. The cleavage-angle is 74° 55′ in calcite and 73° 37′ in sodium nitrate. These two minerals are evidently very closely related in their structure (*cf.* also p. 266), and X-ray analysis has shown that the arrangement of the atoms is the same in both, although their chemical relationship is confined to a similarity in the numbers of atoms in the molecule: $CaCO_3$ and $NaNO_3$; as calcium has no likeness to sodium, nor carbon to nitrogen.

Substances which thus have the same type of composition and resemble one another in their angles and structure have been described by F. Rinne as "isotypic."

Before pursuing further, however, the differences which exist between what are confessedly different minerals, it will be necessary to consider the differences which exist between various specimens of the same mineral.

4. **The Variations in the Composition of a Mineral: Isomorphous Mixtures.**—When minerals of somewhat complex constitution are analysed, it is found very difficult to assign a definite formula even to the most perfect and homogeneous crystals, not only on account of the large number of elements which they contain, but also because the proportions of those elements vary in an apparently erratic manner and never exactly obey the law of definite combining proportions.

Thus the garnets constitute a very sharply defined mineral group. They crystallise extremely well, almost always in rhombic dodecahedra. They resemble each other very closely, and cannot well be confused with any other mineral, in spite of their own differences in colour and in chemical composition.

The following are actual analyses of garnets:

I. A lime-alumina-garnet (grossular) from Monzoni.
II. An iron-alumina-garnet (almandine) from Fahlun.
III. A lime-iron-garnet (melanite) from Långban.
IV. A lime-chrome-garnet (uvarovite) from the Urals.

	I	II	III	IV
SiO_2	39·53	39·66	35·10	35·57
Al_2O_3	20·15	19·66	..	6·25
Fe_2O_3	4·94	..	29·10	
Cr_2O_3	..	..	..	23·45
CaO	33·88	..	26·91	33·22
MnO	..	1·80	7·08	..
FeO	..	39·68	..	..
MgO	1·72	..	..	..
	100·22	100·80	98·19	98·49

With these we may compare the theoretical compositions of the following four compounds which might be expected to be isomorphous :

	$Ca_3Al_2(SiO_4)_3$	$Fe_3Al_2(SiO_4)_3$	$Ca_3Fe_2(SiO_4)_3$	$Ca_3Cr_2(SiO_4)_3$
SiO_2	40·01	36·22	35·47	36·01
Al_2O_3	22·64	20·49	..	..
Fe_2O_3	..	..	31·42	..
Cr_2O_3	..	..	..	30·38
CaO	37·35	..	33·11	33·61
FeO	..	43·29	..	..

Now these minerals, though they differ so considerably in composition, belong without doubt to the same group and are even more closely related in their physical characters than the members of many other mineral groups, such as that of the rhombohedral carbonates given above.

But each mineral, while it approximates more or less to the law of definite combining proportions, as represented by the formula in the second table, differs considerably therefrom.

The differences are clearly in accordance with the principle of vicarious replacement stated above. In the first analysis the alumina is too low, but some ferric oxide is present to account for the deficiency. In the second analysis some of the ferrous oxide is replaced by a proportion of MnO. If, however, the law of definite combining proportions, upon which chemistry appears to be based, is to hold true, how are these replacing constituents present, and what determines their proportions ?

It is true that a large number of mineral analyses are vitiated by the enclosure of one mineral in another. Transparent minerals, even when in the most perfect crystals, are usually found, when examined by the microscope, to contain minute enclosed crystals of other compounds which have to be removed by picking, or by the use of heavy liquids, before a trustworthy analysis can be made. Analysis III, for example, yielded also 0·98 of K_2O, which is probably present as a constituent of some enclosed mineral and does not belong to the garnet itself. But even when all these precautions have been taken, the most homogeneous garnets will give very variable proportions for their vicarious constituents.

If the crystals were liquids it would be natural to suggest that they were mixtures in which the constituents are able to mingle in various proportions, like alcohol and water. Analyses of such mixtures might lead to the most various proportions, but they would always be expressible as a certain amount of alcohol mixed with a certain amount of water. If the liquids were perfectly miscible the mixture would be homogeneous, but the atomic ratios would not be definite.

This is, in fact, now known to be the real explanation of the difficulty. It has been established that certain compounds are miscible in the solid state, exactly as certain substances, like alcohol and water, are miscible in the liquid state, and that they mix to form perfect *crystals*, which may be (to all appearance) as homogeneous as those of a single definite compound.

By allowing solutions containing two or more such compounds in

various proportions to crystallise, the laws of these homogeneous mixtures, or "mixed crystals," have been studied and are now fairly well known.

Now the substances which can form homogeneous mixed crystals of this kind are, with few exceptions, those which are isomorphous, *i.e.* which resemble one another in form and also—more or less closely—in chemical composition. Long before the nature and properties of crystallised mixtures were studied, Mitscherlich, in the course of his researches on isomorphism, made the great discovery that *isomorphous compounds are capable of mixing in varying proportions to form homogeneous crystals.*

The principle of vicarious replacement stated by Fuchs may be regarded as another way of stating the same fact.

This remarkable property has been so completely established by the study of those compounds which are closely related in composition and form, that some authors restrict the term "isomorphous" to substances which are similar in composition and form, *and possess the property of forming homogeneous mixed crystals or "isomorphous mixtures."* For this reason, again, we have preferred to use the term "mineral group" for what is sometimes called an isomorphous series of minerals, since there is not always evidence that all the members of the group can crystallise together as mixtures.

Most of the difficulties encountered in interpreting the variable constitution of a mineral find a satisfactory explanation in Mitscherlich's great principle.

Isomorphous mixtures are especially common in the mineral kingdom, since minerals have rarely been formed as pure isolated compounds, but have generally separated from miscellaneous materials, among which they have been free to mix with isomorphous substances.

The nature of such mixtures can be very easily studied by laboratory experiments upon soluble salts. Thus, if A and B be two substances which are isomorphous in the most rigid sense, like $ZnSO_4 . 7H_2O$ and $MgSO_4 . 7H_2O$, which are similar in composition and nearly identical in form, they are capable of forming crystals *of nearly the same form as their own*, whose chemical composition may be represented as $mA + nB$, where m and n are not necessarily small whole numbers.

Thus crystals may be made which are hydrated sulphates containing both zinc and magnesium, and having a form whose angles are near those of each of these sulphates. Such crystals can neither be called zinc sulphate nor magnesium sulphate, yet their composition is such that they can always be expressed as a mixture of a certain amount of one with a certain amount of the other: $m(ZnSO_4 . 7H_2O) + n(MgSO_4 . 7H_2O)$; they are said to be an "isomorphous mixture" of the zinc and magnesium sulphates. Now the nickel sulphate $NiSO_4 . 7H_2O$, which is a member of the same isomorphous group, may also enter into such an isomorphous mixture, and accordingly it is found that similar crystals of the hydrated sulphate containing zinc, magnesium, and nickel, have the proportions of their constituents so related that the composition may be expressed as $x(ZnSO_4 . 7H_2O) + y(MgSO_4 . 7H_2O) + z(NiSO_4 . 7H_2O)$, or are

isomorphous mixtures of the three sulphates; x, y, and z being different for different specimens.

Similarly any mineral, in crystallising, is capable of mixing with certain quantities of one or more substances isomorphous with itself to form homogeneous crystals. Very few minerals are absolutely simple; most, when carefully analysed, are found to contain small quantities of what were at first regarded as impurities, but are now known to be intermixtures of isomorphous substances.

Thus zinc-blende, ZnS, generally contains a certain percentage of iron: this, however, is present as FeS, and not as metallic iron or as any other compound of iron, for the formula of blende may always be expressed as $x\mathrm{ZnS} + y\mathrm{FeS}$, the percentage of sulphur being exactly sufficient to be combined in the ratio of one atom to one atom with the amounts of zinc and iron present.

Now, in some cases, the compounds of which the mineral is a mixture are known to exist independently as separate minerals; in other cases one or more of these compounds, though not known to exist independently, may be produced artificially; the cubic compound FeS which enters into the composition of most blende does not occur at all as a terrestrial mineral, but crystals of FeS belonging to the cubic system have been prepared artificially.

So many cases have now been established by the discovery or preparation of the missing isomorphous constituents, that even when the separate components have not yet been prepared independently a mineral is still regarded as a mixture of certain isomorphous compounds, one or more of which may be hypothetical.

Thus, if it is found that a mineral of exceedingly variable composition may always be expressed as $x\mathrm{A} + y\mathrm{B} + z\mathrm{C}$, where A and B are known as independent compounds, but C is merely hypothetical, the mineral is regarded as an isomorphous mixture of A, B, and C, although there is nothing to prove the existence of C as a compound isomorphous with A and B except its presence in the mixed crystals.

Garnets which contain any or all of the elements calcium, aluminium, chromium, and iron (ferrous and ferric) may always be regarded as isomorphous mixtures of the following compounds:

(1) $\mathrm{Ca_3Al_2(SiO_4)_3}$	(3) $\mathrm{Ca_3Fe'''_2(SiO_4)_3}$	(5) $\mathrm{Ca_3Cr_2(SiO_4)_3}$
(2) $\mathrm{Fe''_3Al_2(SiO_4)_3}$	(4) $\mathrm{Fe''_3Fe'''_2(SiO_4)_3}$	(6) $\mathrm{Fe''_3Cr_2(SiO_4)_3}$.

In other words, calcium and dyad iron are vicarious elements which may replace each other in the garnets, while aluminium, triad iron, and chromium are also vicarious in this group.

In the analyses given on p. 251,

I may be expressed approximately as
$$73\,\mathrm{Ca_3Al_2(SiO_4)_3} + 13\,\mathrm{Ca_3Fe_2(SiO_4)_3} + 6\,\mathrm{Mg_3Al_2(SiO_4)_3},$$
II as $57\,\mathrm{Fe_3Al_2(SiO_4)_3} + 2\,\mathrm{Mn_3Al_2(SiO_4)_3}$,
III as $5\,\mathrm{Ca_3Fe_2(SiO_4)_3} + \mathrm{Mn_3Fe_2(SiO_4)_3}$,
IV as $50\,\mathrm{Ca_3Cr_2(SiO_4)_3} + 23\,\mathrm{Ca_3Al_2(SiO_4)_3}$.

We see that in I a certain amount of CaO is replaced by MgO ; in II a certain amount of FeO is replaced by MnO ; in III a certain amount of CaO is replaced by MnO ; in IV a certain amount of Cr_2O_3 is replaced by Al_2O_3.

Hence, in addition to the six orthosilicates given above, we have also to suppose that the following may enter equally well into the composition of a garnet:

(7) $Mg_3Al_2(SiO_4)_3$	(9) $Mg_3Fe_2(SiO_4)_3$	(11) $Mg_3Cr_2(SiO_4)_3$
(8) $Mn_3Al_2(SiO_4)_3$	(10) $Mn_3Fe_2(SiO_4)_3$	(12) $Mn_3Cr_2(SiO_4)_3$,

and although none of these silicates is known in a state of absolute purity they are compounds which would be expected to be isomorphous, and they suffice to explain all the variations in the composition of the garnets.

For the sake of abbreviation the intermixture of isomorphous minerals may be regarded as a mutual replacement of vicarious elements, and may be so indicated in the formula. Thus the anhydrous rhombohedral carbonate known by the name of breunnerite contains both magnesium and iron and manganese ; and since these elements are present in varying proportions the formula of the mineral may conveniently be written $(Fe,Mg,Mn)CO_3$—or RCO_3, where R = (Fe,Mg,Mn). Here the elements in the bracket are supposed to be capable of replacing each other in variable proportions ; that is to say, a certain amount of the magnesium may be replaced by the equivalent weight of iron, and so on.

Similarly the minerals of the garnet group may be represented by the " general formula " $R''_3R'''_2(SiO_4)_3$, where R'' = (Ca, Mg, Fe, Mn), and R''' = (Al, Fe, Cr) : a formula which shows that, whatever its composition, a garnet may be regarded as an orthosilicate of three atoms of a divalent and two atoms of a trivalent metal.

5. **Mixture of Dimorphous Substances.**—It sometimes happens that a well-defined mineral is obviously, so far as its composition is concerned, to be regarded as a mixture in varying proportions of two compounds A and B ; and, further, that A and B are known to occur as minerals or may be prepared artificially, but have totally distinct forms.

The mineral cannot, then, it might be urged, be regarded as a mixture of two isomorphous substances, since A and B, though they are of similar composition, crystallise in different forms. For example, a variety of rhombohedral calcite from Leadhills in Lanarkshire contains a variable proportion of lead carbonate, and is for this reason distinguished by the name of plumbocalcite ; it must be regarded as an isomorphous mixture of $CaCO_3$ and $PbCO_3$, since its composition may always be expressed as $mCaCO_3 + nPbCO_3$.

Now $PbCO_3$ is only known to occur in Nature in orthorhombic crystals as the mineral cerussite. How, then, can this enter into an *isomorphous* mixture with calcite ?

The answer to this question is supplied by two other minerals, namely, aragonite and tarnowitzite. Aragonite has the same composition, $CaCO_3$, as calcite, but is orthorhombic. Tarnowitzite is orthorhombic

carbonate of lime $CaCO_3$, containing a variable amount of lead carbonate; it therefore bears the same relation to aragonite as plumbocalcite to calcite, and is to be regarded as an isomorphous mixture of aragonite and cerussite.

We have, then, the following relations—

	Rhombohedral	Orthorhombic
$CaCO_3$	Calcite	Aragonite
$(Ca, Pb)CO_3$	Plumbocalcite	Tarnowitzite
$PbCO_3$	—	Cerussite.

Everything becomes clear if we suppose that $PbCO_3$ may exist in more than one crystalline form. Now two modifications are actually known in the case of $CaCO_3$, which exists as calcite and aragonite; $PbCO_3$ as cerussite is isomorphous with the latter; it may therefore be expected to exist in a second modification isomorphous with the former, and this supposition is supported by the existence of such a mineral as plumbocalcite.

Calcium carbonate, then, is dimorphous, existing both as calcite and aragonite: $PbCO_3$ is dimorphous, existing as cerussite, and also (in plumbocalcite) as a rhombohedral substance capable of entering into an isomorphous mixture with calcite; and the two substances $CaCO_3$ and $PbCO_3$ are said to be "isodimorphous."

Sometimes crystals may be artificially produced which have the same composition as known minerals but a different form, thus proving the dimorphism of the substance; and the form has frequently proved to be precisely that which was required to fill up a gap in some mineral group where mixtures alone are known.

Of this the oxides of arsenic and antimony have generally been quoted as a typical example. Originally Sb_2O_3 was only known in Nature as the orthorhombic mineral valentinite, and As_2O_3 as the cubic mineral arsenolite; the two substances are similar in composition and might be expected to be isomorphous, but the difference in system and form appeared to negative the supposition.

In 1851, however, a cubic variety of Sb_2O_3 was discovered and named senarmontite; this is obviously to be regarded as isomorphous with arsenolite. Now if Sb_2O_3 is isomorphous with As_2O_3 in its cubic modification, it is probably so also in its orthorhombic modification: a consideration which led to the confident prediction of an orthorhombic form of As_2O_3. This prediction was confirmed by the discovery of artificial crystals of As_2O_3 belonging to the orthorhombic system, and having angles very near those of valentinite. Similar crystals have since been found in Nature and are known by the name of claudetite. (Subsequent investigation has shown that claudetite is really monoclinic, though very close in angles to the orthorhombic valentinite.) The two oxides are therefore not only isomorphous, but also isodimorphous. In this instance the isodimorphism is proved by the actual existence of the four sorts of crystals; in the case of calcite and cerussite the isodimorphism is only indicated by the existence of isomorphous mixtures.

So far, the supposition that with isodimorphous substances mixture only takes place between the similar modifications may appear to be a pure assumption; no evidence has been adduced above to prove that cerussite only mixes with aragonite and not with calcite; this fact is really established by the more exact knowledge of the nature of isomorphous mixtures, derived from the study of mixtures artificially prepared in the laboratory, and especially their physical properties.

6. **The Crystalline Form and Physical Properties of Isomorphous Mixtures.**—Firstly, as regards the form of a mixed crystal, it might be expected that the *angles* would be intermediate between those of its two constituents. This indeed appears to be the case in many instances; for example, a rhombohedral carbonate intermediate in composition between magnesite, $MgCO_3$, and chalybite, $FeCO_3$, received the name mesitite as intermediate between these minerals; it has a rhombohedron-angle 72° 46′, that of magnesite being 72° 36′, and that of chalybite 73° 0′. In other groups, however, this is by no means always the case.

Among artificial compounds the orthorhombic mixtures of $MgSO_4 . 7H_2O$ with $ZnSO_4 . 7H_2O$ were examined by Dufet, and the following table gives the results which he obtained for the two salts and seven mixtures:

	Percentage of Mg-salt	Spec. Grav.	(110) : (1$\bar{1}$0)	(010) : (111)
$MgSO_4 . 7H_2O$	100	1·6760	89° 25′	63° 40½′
	78·88	1·7359	89° 17½′	63° 43′
	74·44	1·7472	89° 15′	63° 44½′
	62·70	1·7816	89° 11′	63° 46¾′
	57·59	1·7977	89° 8′	63° 46½′
	42·80	1·8415	89° 3½′	63° 49′
	35·64	1·8604	89° 1′	63° 48½′
	18·11	1·9094	88° 54′	63° 53′
$ZnSO_4 . 7H_2O$	0	1·9600	88° 48′	63° 53′.

Here it will be noticed that the differences of angle are so slight that not much reliance can be placed upon them; they are scarcely beyond the limit of experimental errors, which are usually greater with mixed crystals than with pure substances, as mixtures do not usually form such perfect crystals as do the pure substances.

When, however, we pass to the physical properties, we find from the second column that the specific gravity varies considerably and in a regular manner. In this respect it has been found that the mixed crystals behave as though they were a mere mechanical mixture of the two constituent salts, in which the latter have mixed without change of volume.

In a series of mixtures of this kind it may be proved that if the *specific volumes* of the mixtures $\left(i.e.\text{ the volumes occupied by unit mass, or } \frac{1}{\text{density}}\right)$[1] be compared with their percentage composition (by weight), as in Fig. 397, the values will lie upon a straight line, as at AB. In other words, the difference between the specific volumes of two mixtures will be simply proportional to their difference in composition.

[1] *Cf.* p. 211.

Now by means of heavy liquids, as described on p. 213, it is easy to determine the specific gravity even of very small crystals with accuracy, and that of many such mixtures has been measured. In all the cases which have been investigated the above relation has been found to hold, *viz.* that the specific volume varies directly with the composition of the mixture.

The diagram, Fig. 397, represents the relation between specific volume and composition in mixed crystals of potassium sulphate and ammonium sulphate; the ordinate being taken proportional to the specific volume,

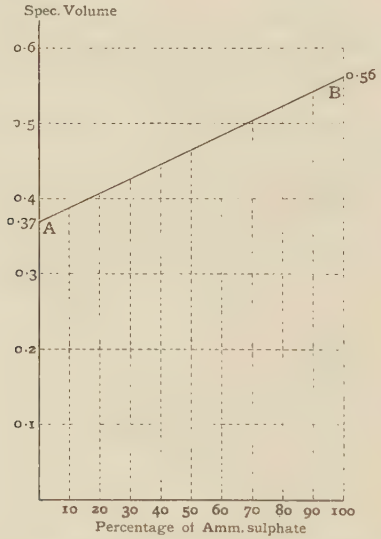


Fig. 397.—Mixtures of Potassium and Ammonium Sulphates.

and the abscissa to the percentage of ammonium sulphate in the mixed crystals examined: we have—

For K_2SO_4	spec. grav. = 2·666	spec. vol. = 0·3751 (A)
,, $(NH_4)_2SO_4$	,, ,, 1·774	,, ,, 0·5636 (B).

Then it is found that the point corresponding to any mixed crystal lies on the straight line AB, and, consequently, if the composition be known the specific volume may be predicted, and *vice versa*.

Thus a mixed crystal containing 20·5 per cent of $(NH_4)_2SO_4$ will have the specific volume 0·4138, and therefore the specific gravity 2·417.

This relation indicates that in mixtures of isomorphous salts there is no change of volume on mixing, but that a given weight of each salt occupies the same volume in the mixture as when pure.

In the case given above the two salts are capable of crystallising together in all proportions; sometimes each of two isomorphous compounds can mix with only small proportions of the other, while mixtures

in anything like equal proportions will not crystallise, at least under ordinary conditions.

Thus acid ammonium phosphate $(NH_4)H_2PO_4$ will form mixtures with varying proportions, up to 20 per cent, of the corresponding potassium salt KH_2PO_4; and, similarly, the potassium salt with small proportions, up to 20 per cent, of the ammonium salt, but intermediate mixtures refuse to form homogeneous crystals.

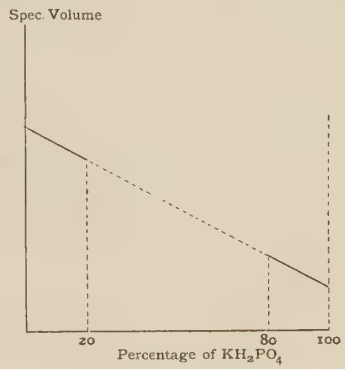


Fig. 398.—Mixtures of Acid Potassium and Acid Ammonium Phosphates.

This state of things is represented by Fig. 398, where the line is interrupted, but here also the one part is a continuation of the other, showing that the mixture is as regular as in the preceding case.

It is otherwise, however, in the case of isodimorphous substances. Thus the salt $MgSO_4 . 7H_2O$ (sp. gr. = 1·677, sp. vol. = 0·596) will crystallise with $FeSO_4 . 7H_2O$ to form mixed crystals containing up to 19 per cent of this salt; and $FeSO_4 . 7H_2O$ (sp. gr. = 1·898, sp. vol. = 0·527) will similarly crystallise with $MgSO_4 . 7H_2O$ to form mixtures containing up to 54 per cent of the latter salt.

But when the corresponding diagram is made by plotting points for the different mixtures, it is found that they lie not upon one but upon two straight lines (Fig. 399). The lower line, when extended, indicates that the sulphate of iron is mixing with a substance whose specific volume is 0·591 (sp. gr. = 1·691), not 0·596, and the upper line indicates that the sulphate of magnesium is mixing with a substance whose specific volume is 0·533 (sp. gr. = 1·875), not 0·527.

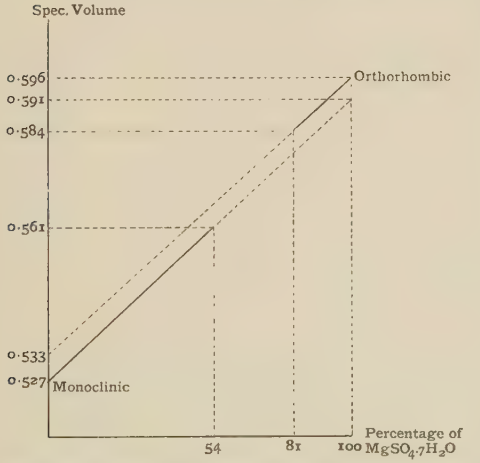


Fig. 399.—Mixtures of Iron and Magnesium Sulphates.

Now the pure salt $MgSO_4 . 7H_2O$ is orthorhombic, and the pure salt $FeSO_4 . 7H_2O$ is monoclinic; the mixed crystals represented by the upper line belong to the orthorhombic system, and those represented by the lower line to the monoclinic system.

We conclude that the unknown substance of specific gravity 1·691 which is mixing with the ferrous sulphate is a monoclinic modification of magnesium sulphate, which is unstable under ordinary conditions, but

capable of entering into mixtures with the isomorphous ferrous sulphate. Similarly, an unstable orthorhombic salt $FeSO_4 . 7H_2O$, of specific gravity 1·875, is isomorphous with ordinary $MgSO_4 . 7H_2O$. Both substances are therefore to be considered as dimorphous, and in fact crystals of the unstable modification of each of the pure salts have occasionally been obtained.

The nature of mixtures of $AgNO_3$ and KNO_3, which both crystallise in the orthorhombic system but with different axial ratios, is shown in Fig. 400.

Each salt can mix with a small quantity of an (unstable) modification of the other, forming crystals of the orthorhombic system, similar in form to the pure salt. Thus the two salts are isodimorphous; but they also crystallise together in *equal* molecular proportions to form a double salt $KNO_3 . AgNO_3$, which is monoclinic and has the specific volume 0·310 (sp. gr. = 3·219). The corresponding point on the diagram lies off the dotted lines representing isomorphous mixtures, the crystalline structure being different from that of either of the pure salts.

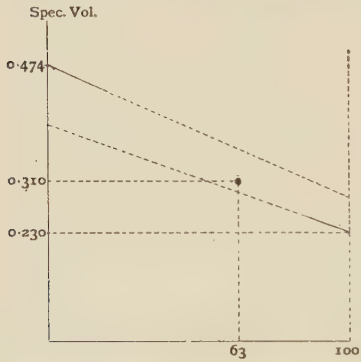


Fig. 400.—Mixtures of Silver and Potassium Nitrates.

Thus when the solutions of two isomorphous salts are mixed the result may be either (1) crystallised mixtures whose specific volumes vary uniformly with their composition as though they were mechanical mixtures, or (2) a double salt whose specific volume cannot be thus deduced from those of the constituents. In the double salt the proportions of the constituents are molecular: in the mixtures they are not necessarily so.

If, instead of the specific volumes, the specific gravities are compared with the percentage composition (by weight), the values for the mixtures will not lie on a straight line, but upon a continuous curve. The specific gravity is thus a *continuous function*, though not a *linear* function, of the composition.[1]

The same is true of the other physical properties of isomorphous mixtures; for example, the refractive indices, the optic axial angle, and the extinction: the value of each property of a mixture is a continuous, though not usually a linear, function of its composition.

In mineralogy the specific gravity and the optical properties are those in which the relations can be most easily traced, and they are of the greatest practical importance.

7. **The Optical Properties of Isomorphous Mixtures.**—When two iso-

[1] If, however, the composition is expressed as a percentage by *volume*, the curve for the specific gravities is a straight line.

morphous cubic substances, two alums for example, crystallise together, the refractive index of the mixed crystals is found to vary continuously with the composition. Fig. 401 summarises observations which were made on mixtures of potash-alum and thallium-alum.

The eight points represent eight mixtures; the distance of each from the vertical axis represents the proportion of thallium-alum in the mixture; its distance above the horizontal axis represents the refractive index. The points are found to lie on a continuous line which is here sensibly straight.

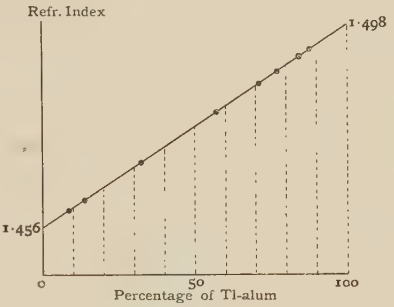


Fig. 401.—Mixtures of Potassium-Alum and Thallium-Alum.

Similarly with uniaxial mixtures, either of the refractive indices ω or ϵ, treated in the same way, will give a continuous line; in biaxial mixtures of orthorhombic crystals three continuous lines can be constructed to represent the variations of the three principal indices α β γ, which in this system belong to fixed directions.

Each refractive index of the mixtures is therefore a continuous function of the composition.

It may of course happen that of two isomorphous uniaxial substances, one is positive and the other is negative. Thus in the case of the two substances A and B, whose optical characters are indicated in I and II, Fig. 402 (representing the axes of the indicatrix), the mixture of increasing proportions of B with A tends to increase the index ϵ in comparison with ω; for some definite mixture, therefore, the two indices for a certain colour

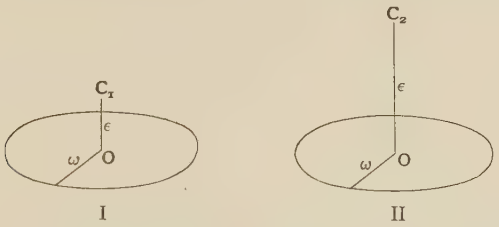


Fig. 402.—Mixture of Negative and Positive Uniaxial Substances.

will become equal, and the crystals will be isotropic for that colour. Thus strontium dithionate, $SrS_2O_6 . 4H_2O$, is negative with weak double refraction; while the isomorphous lead salt, $PbS_2O_6 . 4H_2O$, is positive with stronger double refraction; both salts are hexagonal and possess the symmetry of quartz. A mixture which contains 17·9 per cent of the lead salt is absolutely isotropic for sodium light.

Consider, in the same way, two orthorhombic crystals (Fig. 403) in which the corresponding crystal axes are parallel, the vertical axis in each is the acute bisectrix, and AC in each is the plane of the optic axes;

but I is positive (ac.bis. $= \gamma_1$), and II is negative (ac.bis. $= \alpha_2$). In mixed crystals the three refractive indices corresponding to the directions A, B, C, will be intermediate between those of the pure substances for the corresponding directions; and in a certain mixture two of the indices, for a particular colour, may be equal to one another, and the crystal will, for that colour, be uniaxial.

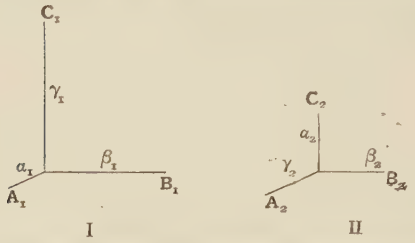


Fig. 403.—Mixture of Positive and Negative Biaxial Substances.

From these two examples it is clear that an isomorphous mixture of two substances may, in monochromatic light, appear to have a physical symmetry higher than that which belongs to either of them.

In the monoclinic and anorthic systems the relations are far more difficult to follow, for not only do the magnitudes and ratios of the refractive indices vary, but also the orientation of the indicatrix within the crystal. Nevertheless the same principle holds good, and the orientation of the indicatrix, like all the physical properties, changes gradually with the proportions of the constituents.

The really important feature of isomorphous mixtures is that they are homogeneous crystals and therefore possess a definite indicatrix, whereas a mere mechanical mixture of crystalline particles of one substance with crystalline particles of another transmits light between crossed nicols without definite extinctions or interference-figures, and is said to exhibit "aggregate polarisation."

In most crystals the positions of the optic axes are far more easy to determine than the refractive indices, and since these positions are functions of the latter they are also themselves continuous functions of the composition, like the specific gravity or any other physical character. Thus in mixtures of potassium sulphate, K_2SO_4, with ammonium sulphate, $(NH_4)_2SO_4$,—both orthorhombic salts—the following results have been obtained:

In K_2SO_4 the optic axes are in the plane (100), the acute bisectrix is perpendicular to (001), and the axial angle (2V) is 67° 20′.

In mixtures, as the proportion of the ammonium salt in the crystals increases, the axial angle diminishes, until with 19 per cent the crystals become uniaxial, the optic axis being perpendicular to (001); as the proportion is still further increased the optic axes open out again, but in the plane (010), which remains the plane of the optic axes until the pure ammonium sulphate is reached, the axial angle increasing until in $(NH_4)_2SO_4$ the perpendicular to (001) is the obtuse bisectrix and the axial angle about this line ($2V_o$) is 127° 48′.

The change closely resembles that which may be produced by change of temperature in a single crystal of some substances, such as gypsum (see p. 592).

In the case of monoclinic and anorthic minerals the optic axial angle

and the extinction-angles of certain faces are practically the only characters available, since the determination of the principal indices and of the orientation of the indicatrix in this systems is a tedious process.

8. **Optical Properties of the Felspar Group.**—Among transparent minerals no group has been so thoroughly studied as that of the felspars.

These minerals are the most important constituents of the igneous rocks, whose nature, in fact, depends very largely upon that of the felspar which they contain. The crystals are generally very small and without faces, since they are embedded among other minerals. To identify the particular felspar of any igneous rock is always a problem of the utmost importance to the geologist.

The specific gravity can be determined by heavy solutions, by which, also, the felspar can be separated for analysis from the other minerals of the rock when this has been crushed to a powder. But for ordinary identification the rock is cut into thin transparent sections and the various

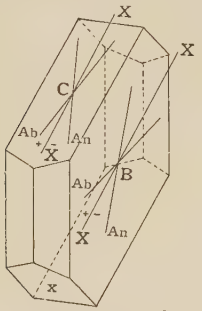


Fig. 404.

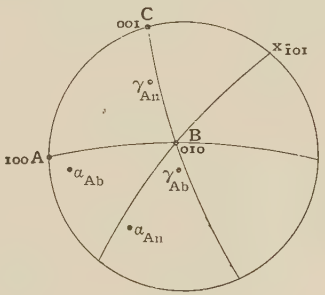


Fig. 405.

Optical Properties of Plagioclase Felspars.

minerals are identified by their optical properties under the microscope. And so it happens that, as regards composition, specific gravity and all the optical properties, the felspars have been exhaustively studied; they are up to the present the only group of minerals in which the continuous variation of physical properties has been successfully traced throughout the group and has been proved to be such as is completely characteristic of an isomorphous mixture. We can therefore take them as affording a perfect example of the relations between the various properties of minerals belonging to a group whose members are not only isomorphous as regards form, but mingle to form homogeneous mixtures.

It has been established by Tschermak and others that those felspars which contain both soda and lime (known as the plagioclase felspars) can always be regarded as isomorphous mixtures of the soda-felspar, albite, $NaAlSi_3O_8$, with the lime-felspar, anorthite, $CaAl_2Si_2O_8$.

In spite of their dissimilarity in composition these substances undoubtedly form mixed crystals in the most various proportions. Both albite and anorthite belong to the anorthic system and may crystallise in the form of Fig. 404.

Both possess perfect cleavages parallel to the faces B (010) and C (001).

In albite the cleavage-angle BC = 86° 24′.
„ anorthite „ „ 85° 50′.

The directions of the indicatrix-axes are shown on the stereographic projection of Fig. 405.

γ_{Ab} is the acute positive bisectrix of albite.
α_{Ab} is the obtuse negative bisectrix of albite.
α_{An} is the acute negative bisectrix of anorthite.
γ_{An} is the obtuse positive bisectrix of anorthite.

The true axial angle 2V, about the positive bisectrix, is about 77° in albite and 103° in anorthite.

Hence, when cleavage-flakes are examined in convergent light :—

The face B of albite shows the positive bisectrix nearly central, with the two optic axes beyond the edge of the field of view (Fig. 672).

The face B of anorthite shows one optic axis on the edge of the field of view (Fig. 674).

The face C of albite shows no interference-figure (in white light).

The face C of anorthite shows one optic axis on the edge of the field of view (Fig. 676).

The extinction-directions on C and B, measured with reference to a line XX parallel to their edge of intersection, are shown in Fig. 404 ; the inclinations for albite are in one direction, which is by convention called positive ; those for anorthite are in the other or negative direction.

Now between albite and anorthite a whole series of intermediate felspars has been examined ; the gradual and regular variation of their properties is shown in the following table, in which the composition of certain members of the group is expressed as a mixture of a certain number of molecules of albite (Ab) with a certain number of molecules of anorthite (An).

	Composition	Spec. Grav.	Extinction-angle on C	Extinction-angle on B	Mean Refractive Index β
Albite	Ab	2·624	+ 4° 30′	+19°	1·534
	Ab_3An	2·659	+ 1° 4′	+ 4° 36′	1·546
	AbAn	2·694	− 5° 10′	−16°	1·558
	$AbAn_3$	2·728	−17° 40′	−29° 28′	1·570
Anorthite	An	2·758	−37°	−36°	1·584.

Since γ is the acute bisectrix for albite and α that for anorthite, the axial angle (2V) of one or more of the intermediate mixtures must be 90°, and the acute and obtuse bisectrices cannot then be distinguished. This seems to be the case for a mixture of composition near Ab_4An.

Similarly, for one mixture the extinction-angle on B, and for another that on C, must be 0°. A mixture near Ab_2An has nearly straight extinction both on B and on C.

If the specific gravity, the extinction-angles, and the refractive indices for the mixtures were plotted out as in the preceding section, continuous

curves would be obtained, from which the characters of any desired mixture might be predicted. Similarly, in Fig. 405, the γ bisectrix would gradually migrate from γ_{Ab} to γ_{An}, and α from α_{Ab} to α_{An}, as the composition gradually changed from Ab to An.

It will be noticed that in the felspar group we have to regard $Na'Si''''$ as vicarious with $Ca''Al'''$. Although albite and anorthite can thus hardly be regarded as similar in composition, and can therefore scarcely be called isomorphous in the original sense of the word, their close similarity in form and cleavage, combined with the fact that they form homogeneous mixtures in all proportions and that the properties of the mixtures vary regularly with their composition, shows clearly that they are very closely related; and they form one of the best known examples of a mineral group. An extension of the meaning of isomorphism to include such cases is fully justified.

9. **Intergrowths and Overgrowths of Different Minerals.**—The homogeneous mixture of the constituents in a mixed crystal is clearly shown in cases where one is colourless and the other coloured, by the uniform coloration of the crystals. This was pointed out by Retgers, who found that the dark purple salt, potassium permanganate, $KMnO_4$, mixes with the colourless perchlorate, $KClO_4$, which is isomorphous with it, to form uniformly coloured crystals.

Now nothing is more common among minerals than to find perfectly clear homogeneous crystals of the most widely different colours, although they belong to the same mineral. Garnet is not only colourless but also, and much more often, black, brown, yellow, red, or green. The smallest proportion of a coloured constituent may greatly alter the appearance of the substance.

The almost universal occurrence of mixed crystals in the mineral kingdom makes it probable that the equally common variations of colour are often to be ascribed to the intermingling of variously coloured isomorphous compounds.

If the composition of the mixture changes during the growth of such crystals the colour will also change, and consequently the inner and outer layers will be differently coloured, giving rise to a "zoned" crystal. Zonal "overgrowths" of this kind are frequently observed in minerals; in tourmaline, for example, a prism of one colour often seems to be enclosed within a prism of another colour, or the same crystal may be differently coloured at its two ends.

The frequent occurrence of such a zonal structure in mixed crystals is due to the fact that when a solution of two isomorphous substances crystallises, the mixed crystals which are formed do not usually have the same composition as the solution, but contain a larger proportion of one of the constituents. Hence, as the crystals grow, the composition of the solution will change, becoming gradually poorer in that constituent; and the later and outer layers of the crystals will therefore also be poorer in it than those first formed.

It must be remembered that mixed crystals may not only be formed by crystallisation from a common solvent, as with the alums, etc., but

may result from the cooling of a fused mixture, as in the crystallisation of a slag, an igneous rock, or an alloy, or even from the condensation of mixed vapours, in sublimation. Zoned crystals may be formed in any of these ways, and an example is afforded by the soda-lime-felspars of many igneous rocks.

Here, a crystal having a certain extinction-angle may be enveloped by layers having different extinction-angles, corresponding to different composition, and forming a zoned crystal in which the zonal structure is only visible between crossed nicols and reveals itself in a section by the extinction-shadow that passes across the crystal, zone by zone, as the microscope stage is rotated.

If a crystal of chrome-alum be immersed in a saturated solution of common alum, a slight re-solution of the crystal will take place, but will be immediately succeeded by a crystallisation of the latter salt, which proceeds to grow in parallel position upon the former; ultimately the crystal of colourless potash-alum will contain, as a coloured kernel, the crystal of chrome-alum: here there has been a parallel overgrowth of the one of two isomorphous substances upon the other.

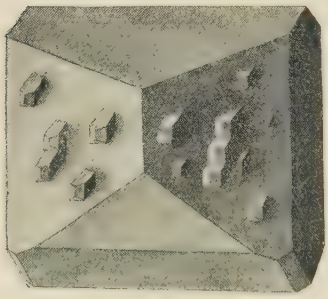


Fig. 406.—Albite in Parallel Position upon Orthoclase.

In other cases the overgrowth may be of such a sort that isolated crystals of a substance A are deposited upon a crystal of an isomorphous substance B, so as to be all parallel to the latter. Thus crystals of one felspar sometimes lie in parallel position upon a crystal of another felspar (Fig. 406).

As in the mixtures, which represent the intergrowth of two substances to form a single crystal, so also the parallel growth of crystals of one sort upon another generally takes place between those which are analogous in chemical composition; but it may also take place between those in which the chemical relationship is very slight.

Thus sodium nitrate, $NaNO_3$, is almost identical with calcite, $CaCO_3$, in angles, in cleavage, in its mode of twinning and its optical properties, and both possess also a very strong double refraction. The two substances are not known to form mixed crystals,[1] but if a drop of sodium nitrate solution be placed on a fresh cleavage-face of calcite, the little rhombohedra of the nitrate will be seen to grow in almost perfect parallelism upon the calcite, as in Fig. 407.

That this is not a mere chance relation is proved by the fact that KNO_3, which is isodimorphous with $NaNO_3$, crystallises in the orthorhombic system, with angles and twinning almost identical with those of aragonite, and is itself capable of crystallising in parallel position upon aragonite. Hence if the word isomorphism is to be allowed to include

[1] This may possibly be due to the fact that they differ widely in solubility, and cannot be fused together without decomposition.

such cases, the nitrates $R'NO_3$ must be called isodimorphous with the carbonates $R''CO_3$.

Their mutual relationship appears to consist in the fact that the two molecules contain the same number of atoms and that these are similarly arranged in the crystal (as has been proved by X-ray analysis), rather than in any close chemical similarity.

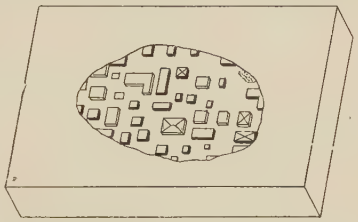


Fig. 407.—Sodium Nitrate crystallising on Calcite.

It is reasonable to suppose that if two structures are to fit together the particles of which they consist must not only be similarly arranged but (while not necessarily in contact or of the same size) must occupy nearly equal volumes, *i.e.* their centres must be nearly equally distant from one another.

Now the density (or specific gravity) of a mineral is proportional to the weight of its particles and inversely proportional to the volume which these occupy; and as the arrangement is presumably the same in a series of isomorphous substances, the weight of the particles may be expected to be proportional to the molecular weight of the substance. Hence it may be supposed that the volume occupied by a particle may be represented by the molecular volume, *i.e.* by the product of the specific volume × molecular weight, or by the ratio $\frac{\text{molecular weight}}{\text{density}}$.

It has been shown by Barker in certain cases, such as that of the alkali haloids, that parallel growths similar to those of sodium nitrate on calcite are only formed when the two substances have nearly the same molecular volumes. In the case of calcite and sodium nitrate also, the molecular volumes are nearly equal (calcite = 36·8, sodium nitrate = 37·6).

The question of the structure of crystals will be more fully considered in Book IV, but it may be mentioned here that these results are confirmed by the direct measurements made by means of X-rays.

10. **Intergrowths and Overgrowths of the same Mineral.**—In all the mixed or associated growths considered above the features are much the same; two compounds possessing not only nearly the same form but nearly the same internal structure (as is proved by their similarity of cleavage) can crystallise together, either one upon another, or with such complete interpenetration that they unite to make a crystal which is practically homogeneous. In such a homogeneous mixture the properties are such as might be expected to result from an intimate mechanical mixture of the one substance with the other; they can be predicted by adding the effect of one to the effect of the other in proportion to the amount of each; this is indicated by the gradual change of a general property, *e.g.* the specific gravity, as the composition gradually changes. Further, the particles cannot be regarded as mixed in confusion, as they would be in a mere mechanical mixture, but must be placed in such a way that those of the one substance are arranged as nearly parallel to those of the other as is compatible with the slight difference of form; this is indicated by the

gradual change of the crystallophysical properties, such as an extinction-angle or a particular refractive index. When, for example, each of the three refractive indices of the intermediate felspars is found to be a continuous function of the composition, it is clear that in the mixtures of albite with anorthite the indicatrix of each of the constituents maintains the same orientation in all the mixtures. The same conclusion may be drawn from the fact that the cleavage generally remains unchanged in a series of isomorphous mixtures. In other words, we are dealing with a mechanical mixture in which the particles are arranged in an orderly manner, and parallel to each other, like those of a simple crystal.

Now all these features suggest very forcibly an analogy with twinning, especially the hemitropic types; there, also, two crystals are associated either one upon another or by interpenetration.

If it be supposed that a crystal consists of particles arranged in a uniform and orderly manner, twinning may well be due to the fact that after one individual has been turned into the twin-position the orderly arrangement of its particles is nearly the same as before; in a juxta-position-twin the arrangement may only be the same in the composition-plane, where the two individuals come into contact;[1] in an interpenetration-twin the arrangement may be nearly the same throughout.

This explanation seems very reasonable, and the resemblance between twins and isomorphous mixtures is very close in the case of pseudo-symmetric crystals. In a mimetic mineral like aragonite it is clear that the crystal possesses nearly hexagonal symmetry about its vertical axis, so far as its external form is concerned, and probably, therefore, in its internal structure also. Hence a rotation of about 60° round the vertical axis (Fig. 388) will bring the structure *nearly* into coincidence with itself, and the two individuals will be free to intermingle. In a pseudo-symmetric crystal the resemblance is even closer. Thus in the case of boracite the structure is so nearly that of a cubic crystal that it is nearly coincident with itself after an appropriate rotation about any of the axes of pseudo-symmetry. Hence during crystallisation the particles are free to deposit themselves either in parallel or in twin-position, and the result is so nearly a uniform cubic crystal that the mineral can only be distinguished from a cubic one by its optical properties.

Again, the anorthic crystals of microcline (p. 518) very closely resemble the monoclinic crystals of orthoclase in their angles as well as in their specific gravity and optical properties, except that the extinction-angle on $C = 15° 30'$, and that they are intimate interpenetration-twins. Now it has been shown by Mallard that if the twin-lamellation were sufficiently fine the optical properties would be indistinguishable from those of orthoclase. Hence it is possible that the two minerals may really be identical, differing only in the fineness of the pseudo-symmetric twinning.

11. **Properties due to the Association of similar Crystalline Structures.**—Many of the features of crystallised minerals which at first appeared to be

[1] This may be compared with the regular growth of rutile prisms on the basal plane of hæmatite, described on p. 96.

anomalous can now be explained as due to the *intergrowth and overgrowth of nearly identical structures.*

Crystals clearly grow by the accretion of particles of some sort; that the arrangement of the particles is uniform and regular, and that they are parallel to each other, is clear from the homogeneity of crystals, as indicated by their cleavage and other physical properties, and from their action on X-rays. Twinning will then be due to the fact that the same particles may fit almost equally well into the structure in the twin-position, or positions, as in the parallel position.

Similarly if two different compounds crystallise in structures which are nearly identical they may mix to form either regular overgrowths or, when the structures are sufficiently similar, isomorphous mixtures. In the latter case there is generally a more or less close relationship between the two substances as regards chemical composition.

The intermixture may in any case be of more than two kinds of particles; those felspars, for example, which contain potassium as well as sodium and calcium, are mixtures of albite, anorthite, and a potassium-felspar.

Again, the particles of a given compound may be arranged in different ways and give rise to more than one structure (polymorphism), but in the case of isodimorphous compounds intergrowths of the nature which we are considering will only take place between the similar structures.

It may be expected that for mixed crystals, as for parallel growths, the particles of the constituents must occupy nearly the same volumes if the two structures are to fit together.

The molecular volume might therefore be expected to be the same, or nearly the same, in substances which readily form isomorphous mixtures, although the specific gravities may be widely different. Thus, in the case of magnesite and chalybite, which readily form mixtures (Mg, Fe)CO_3, the specific gravity of $MgCO_3$ is 2·96, that of $FeCO_3$ is 3·86; but the molecular volumes are nearly the same (magnesite 28·5, chalybite 30·0).

So also albite and anorthite possess the same molecular volume, 101; and it is to this, combined with their similarity of structure, as indicated by their crystalline form and cleavage, that their perfect miscibility in spite of a dissimilarity of composition is probably due.

In mixed crystals, as we have seen, the physical properties are a direct additive result of the chemical composition; but when two constituents unite in molecular proportions to form a double salt, this is not the case; the form and symmetry of the double salt are usually quite unlike those of its constituents, so that the physical properties are not comparable. Thus the monoclinic potassium-silver nitrate, $KNO_3 . AgNO_3$ (p. 260), does not resemble either of its constituent (orthorhombic) salts. In some cases two isomorphous substances show a tendency to crystallise together in molecular proportions to give crystals resembling them in form. Such mixtures are sometimes regarded as double salts, as in the case of dolomite, $CaCO_3 . MgCO_3$; but it is possible that they may only represent specially stable points in a series of isomorphous mixtures, when the numbers of the two kinds of molecules are equal, or in some simple

proportion. In alstonite, which resembles aragonite and witherite in form and is usually regarded as an isomorphous mixture (Ca, Ba)CO_3, the composition varies in different specimens, but the proportion of $CaCO_3 : BaCO_3$ is usually near 1 : 1.

$CaCO_3$ and $BaCO_3$ also unite in molecular proportions to form a double salt $CaCO_3 . BaCO_3$ (barytocalcite) which is monoclinic.

Enough has been said in the preceding sections to show how it is that one and the same mineral may vary quite widely in its properties and in its composition, since it may not only be a pseudo-symmetric twin, and so may possess apparently anomalous physical characters, but it may further be a homogeneous mixture of several definite constituents, and may apparently defy the law of simple atomic proportions. All these apparent anomalies and inconsistencies are to be regarded as the result of the crystalline structure, and are due to the fact that two or more nearly identical structures may unite to form a single crystal.

Although in the case of most minerals the constituents are not known and cannot be isolated, yet the variations which they produce must be of an orderly and regular character; it is mainly by a study of these variations (as has been done for the felspars) that the nature of the constituents and their properties will be traced. The study of the properties of minerals will then be the study of the nature and the arrangement of the crystalline particles of which the solid crust of the earth is built up.

BOOK IV

THE INTIMATE STRUCTURE OF CRYSTALS

CHAPTER I

THEORIES OF CRYSTAL STRUCTURE

1. **The Space-lattices.**—The theory of crystal structure which was devised by Haüy has been alluded to on p. 21 ; it is based upon cleavage, and leads to the law of rational indices. We cannot, of course, believe that a crystal with cubic cleavage really consists of small cubes packed together, as in Fig. 37, so as to fill space without interstices ; but there are other ways of interpreting the structure. For example, let the cubes be replaced by spheres inscribed in them ; this would give a stack of equal spheres, each of which is in contact with six neighbours, Fig. 408, and the cubic arrangement is still the same as in Fig. 37.

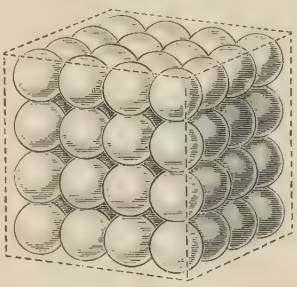


Fig. 408.

Or, again, each cube may be replaced by a small particle placed at its centre, and the structure becomes a cubic assemblage of particles which are not in contact at all, but may be regarded as held together by their own forces of mutual attraction and repulsion.

An identical structure is obtained by placing particles at the corners of the cubes, instead of at their centres (Fig. 409).

In such a structure the particles all lie along straight lines ; and the structure fulfils the following conditions : (1) the line joining any pair of particles, if prolonged in both directions, will carry a series of particles at intervals equal to that which separates the pair selected, and (2) the particles will be distributed in precisely the same way along a parallel line drawn through any other particle of the assemblage. Such a structure is therefore in complete harmony with the nature of a crystal as revealed by its physical properties ; for it is homogeneous, *i.e.* alike in all its parts, and all parallel lines of particles are similar. Further, the particles are all distributed uniformly in planes ; the plane containing any three particles, if produced, will carry a series of particles uniformly distributed at the same intervals ; and these planes, like the faces of a crystal, obey the law of rational indices. The structure is therefore in complete harmony with a crystal also as regards its geometrical properties.

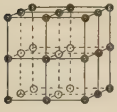


Fig. 409.

A structure fulfilling the above conditions is called a "space-lattice" (German, *Raumgitter* ; French, *réseau*) ; it is a net-like structure in which the particles are situated at the corners of parallel and equal parallelepipeda.

The structure of Fig. 409 may be called that of the cube, since it is obtained by dividing space into cubic cells and placing a particle at the corner, or centre, of each cell.

Now the simple cubic lattice is not the only one which satisfies the requirements of a crystal.

Between the years 1835 and 1856 Frankenheim and Bravais independently solved the problem—"How many kinds of space-lattice can be constructed?" and found the number to be fourteen. These are as follows:

The Fourteen Space-lattices

The cube	Fig. 410 (i).
The centred cube, *i.e.* the cube with a particle at each of its corners and one at its centre	,, ,, (ii).
The cube with centred faces, *i.e.* the cube with a particle at each of its corners and one at the centre of each of its faces	,, ,, (iii).
The square prism (*cf.* Fig. 123)	,, ,, (iv).
The centred square prism	,, ,, (v).
The prism of 120° (*cf.* Fig. 413)	,, ,, (vi).
The rhombohedron	,, ,, (vii).
The orthorhombic prism (*cf.* Fig. 145)	,, ,, (viii).
The centred orthorhombic prism	,, ,, (ix).
The rectangular parallelepiped (*cf.* Fig. 144)	,, ,, (x).
The centred rectangular parallelepiped	,, ,, (xi).
The clinorhombic prism (*cf.* Fig. 211)	,, ,, (xii).
The monoclinic parallelepiped (*cf.* Fig. 209)	,, ,, (xiii).
The triclinic parallelepiped (*cf.* Fig. 220)	,, ,, (xiv).

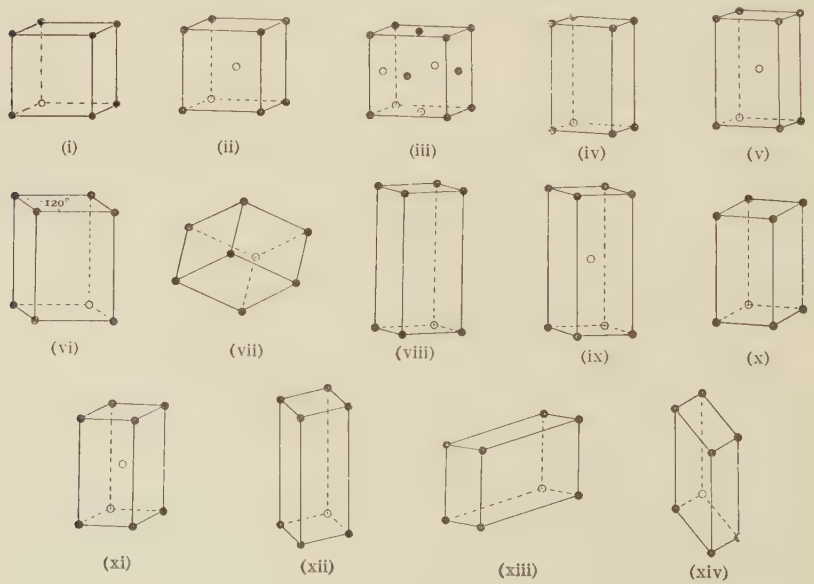


Fig. 410.—The Fourteen Space-lattices.

The " centred " lattices, such as (ii) the centred cube, while themselves fulfilling the conditions for a lattice, are composed of two similar simple (in this case cubic) lattices interpenetrating in such a way that the particles of one of them occupy the centres of the cells of the other.

Such a lattice corresponds to a stack of parallelepipeda which have the form, in the above instance, not of a cube but of a rhombohedron with an angle of 60°, consisting of three adjacent faces of the dodecahedron, such as (110), (101), (011), together with the faces parallel to them.

The cube with centred faces (iii) consists, similarly, of four simple cubic lattices interpenetrating. The corresponding parallelepipedal cell is a rhombohedron with an angle of 109° 28′, obtainable from the octahedron by omitting two opposite (parallel) faces. This arrangement is equivalent to a stack of equal spheres packed together as closely as possible (Fig. 411), in which (as in a pile of balls) every sphere is in contact with twelve others.

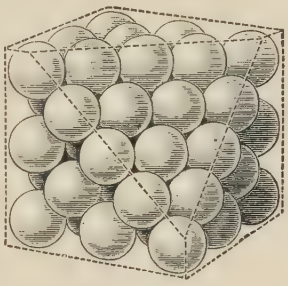


Fig. 411.

The fourteen space-lattices above described all possess the homogeneity and the anisotropic character (p. 119) of crystals, and planes passing through any three of their particles all obey the law of rational indices. But they possess a still more remarkable feature—each lattice has the symmetry of one of the crystal systems, and all the six systems are represented among them, as follows :

i-iii	Cubic System.
iv-v	Tetragonal System.
vi-vii	Hexagonal ,,
viii-xi	Orthorhombic System.
xii-xiii	Monoclinic ,,
xiv	Anorthic ,,

It will be noticed, however, that only the symmetry of the holosymmetric classes is represented among the lattices ; if the remaining classes are to be accounted for, some additional supposition will have to be made. This may be done in two ways, either (1) by supposing the symmetry to depend not only upon the arrangement of the particles but also upon the symmetry of the particles themselves, or (2) by considering new arrangements of particles which are not lattices.

(1) *Possible Differences in the Symmetry of the Constituent Particles.*—In the lattices there is no distinction between opposite directions—*i.e.* between a forward and a backward direction—along any line of particles ; and for this reason they cannot display the symmetry of any of the polar classes of crystals described above. But suppose, for example, that the particles themselves are pear-shaped, and are arranged along one set of parallel lines with all their sharp ends pointing in one direction and their blunt ends in the other, then the structure may be expected to display a certain polarity in the direction of those lines.

Or, again, in the cubic lattice of Fig. 409, let the particles be all parallel tetrahedra whose edges are parallel to the diagonals of the cube-faces; then if account be taken, not only of the arrangement of the particles, but also of their own symmetry, the symmetry of the structure as a whole will be tetrahedral, *i.e.* di-tesseral polar (Class XXXI).

In some such way it will be possible to find representatives of most of the thirty-two classes. Bravais attributed the various degrees of symmetry within a crystal system to the nature of the constituent particles.

(2) *Homogeneous Arrangements which are not Space-lattices.*—Haüy himself pointed out that the cleavage does not always lead to figures with parallel faces like the fourteen cells considered above. Take, for example, a cleavage parallel to the faces of the hexagonal prism. Let Fig. 412 represent the base of the hexagonal prism; cleavage parallel to its edges will divide it, not into hexagons, but into triangles, as shown in the figure. It is true that the triangles may be grouped together in pairs to form rhombs of 120° like A B C D; but this is a purely arbitrary process, and if the cleavage is to represent the structure we must regard it as based,

Fig. 412.

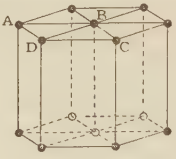


Fig. 413.

Fig. 414.

not upon the rhombic or hexagonal prism, but upon the triangular prism. Particles placed at the *corners* of these prisms, as in Fig. 413, may equally well be regarded as placed at the corners of the rhombic prisms of 120° like A B C D, and the structure is the lattice (vi) of Fig. 410.

But the triangular prisms are in reality of two distinct sorts: half of them have the vertex pointing upwards in Fig. 412, while the other half point downwards. If, as in the case of the cubic structure, each prism be replaced by a particle situated at its centre, the arrangement is not a lattice at all, but the hexagonal or bee's-cell structure of Fig. 414. Even if the particles of Fig. 414 are all similar in nature, they are not similar in position, for one half (●) are situated vertically above, and the other half (○) vertically below an adjacent particle. The structure consists in fact of two space-lattices, ● and ○, each like Fig. 413, which have been thrust into one another in such a way that *about every point of the system the disposition of the remaining points is exactly the same* (although it may not always face the same way). In this sense such a structure is homogeneous; it is the same throughout, and is thus in harmony with the physical requirements of a crystal, although it is not a space-lattice.

2. **The Regular Point-systems.**—To construct a system of points, like the bee's-cell arrangement, which fulfils this condition, it is necessary to choose one of the fourteen space-lattices described above and to take two or more such (identical) lattices and thrust them into one another in such a way as to satisfy the above condition for homogeneity.

The number of arrangements of this sort which can be constructed was investigated by Sohncke in 1879, and is found to be sixty-five. These are known as the " regular point-systems."

An example of such a structure, the " trigonal columnar system " (No. 17 of Sohncke), is shown in Fig. 415, in which the circles represent points or particles in the plane of the paper, other planes similarly beset with particles being situated at equal distances above and below that plane. The structure is composed of three similar interpenetrating lattices (*a*, *b*, *c*), each like No. vi of Fig. 410.

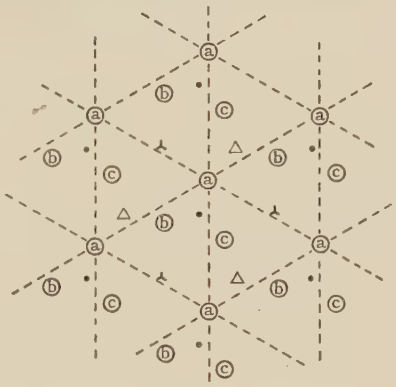


Fig. 415.

In such a point-system all the points are precisely alike in character and are interchangeable, so that if the system be either moved parallel to itself in such a way that one of its points comes into the position previously occupied by another point of the same constituent lattice, or if it be rotated through the proper angle about one of its axes of symmetry, it presents precisely the same appearance as it did at first.

The homogeneity of such a structure consists in the uniform repetition of its parts throughout space, as indicated by the existence of such " coincidence-movements."

In the structure of Fig. 415 the coincidence-movements are (1) a translation through a distance *aa* along a line joining any two points *a*, in the plane of the paper (*e.g.* along the dotted lines), or perpendicular to that plane; (2) a rotation through 120° about one of the threefold axes which pass through the points • ⅄ △.

The sixty-five regular point-systems obtained by Sohncke (of some of which the bee's-cell structure of Fig. 414 is a specialised case) comprise all the possible types of homogeneous arrangement of points or particles which are all of one kind.

Among them most of the thirty-two classes of crystals may be represented without any assumption being made regarding the symmetry of the constituent " points " or particles, except that this must be sufficiently high to conform to the symmetry characteristic of the structure (as would be the case, for example, with simple points or with spherical particles). In the case of crystals with polar symmetry, however, Sohncke was driven, like Bravais, to assume the existence of a polar character in the particles; and, in order to avoid this necessity, and to cover the case of the dioptase class, which was not represented among the sixty-five point-systems, he devised a modified theory, according to which a crystal might be composed of two or more distinct point-systems interpenetrating, each composed of a separate set of particles which might be different from the others

in kind, but all having the same set of coincidence-movements in common.[1]

By means of this extension of his theory Sohncke was able to construct homogeneous arrangements of particles having the symmetry of each of the thirty-two classes.

In the application of the point-systems to crystals the points do not necessarily represent atoms, or molecules, of the crystal; but every point of the system must have the same relation to the surrounding atomic or molecular structure as has every other point of the same system. In other words, the arrangement of the atoms, or molecules, of the crystal when viewed from any one point must present precisely the same appearance as when viewed from any other point of the same system.

If, in a particular crystal, one of the points marks the position of an atom of a certain kind, then similar atoms will be found at every other point of the same system; and all such atoms will be similarly related to the surrounding atoms of the crystal.

In Sohncke's extended theory the points of each of the several interpenetrant point-systems may be supposed to represent a set of atoms, all of one kind; and the following definition of a crystal has been proposed by Groth:

"A crystal, considered as indefinitely extended, consists of n interpenetrating regular point-systems, each of which is formed from similar atoms; each of these point-systems is built up from a number of interpenetrating space-lattices, each of the latter being formed from similar atoms occupying parallel positions. All the space-lattices of the combined system are geometrically identical, or are characterised by the same elementary parallelepiped."

In some few of the thirty-two classes it is necessary to suppose that the particles of which the two or more interpenetrant point-systems are formed are of two kinds, A and B, which are mutually enantiomorphous; and that these are so placed in the structure as to be related to one another about an alternating axis or a centre of symmetry.

The appearance of the structure as viewed from a point A then differs from that as viewed from a point B as a right hand differs from a left hand.

The dioptase class, with its hexagonal axis of alternating symmetry, is a case in point. Here, as in all such problems, the question of the possible structure may be treated by first uniformly partitioning space into cells, or filling it with solid figures, and then replacing each of these cells or figures by a particle.

Fig. 416 represents a structure (of solid figures) which possesses an alternating hexagonal axis; it consists of rhombohedra, each of which is divided into six segments, but in each rhombohedron the three upper segments (R) differ from the three lower segments (L), although they are similar figures. An upper segment bears to a lower segment the same relation that a right hand bears to a left hand; they are enantio-

[1] For example, in one class (Class IV, Digonal Polar), each of the two constituent systems has a plane of symmetry, but the planes, though parallel in the two systems, are not coincident, and the structure as a whole has no plane of symmetry.

morphous figures; one is the reflection of the other. Hence, if each segment of Fig. 416 be replaced by a particle in such a way as to preserve the symmetry of the structure, the particles must be of two sorts, and

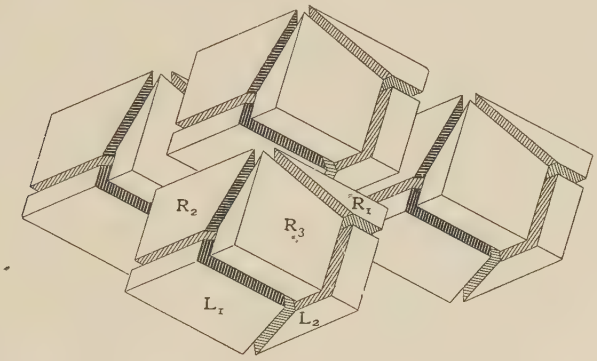


Fig. 416.

must bear an enantiomorphous relation to each other.[1] Each rhombohedron, and therefore the whole structure, possesses centro-symmetry, but no planes of symmetry are present and the structure has the symmetry of dioptase.

3. **Enantiomorphous Repetition: the 230 Types of Crystal Structure.**— The introduction of two sets of enantiomorphous particles in this way is equivalent to adding to the "coincidence-movements" of Sohncke the enantiomorphous "coincidence-operations" of reflection over a plane and of repetition about an alternating axis or a centre of symmetry, in such a way that if the structure is submitted to a certain group of operations its appearance is precisely the same after the process as before it.

A structure characterised by a certain group of operations (including coincidence-movements) may be constructed by taking a single particle and submitting it successively to the several operations of the group, and repeating this process indefinitely.

All the conceivable types of homogeneous arrangement which can be developed in this way, or (in other words) can be obtained by combining space-lattices composed either of one kind or of two enantiomorphous kinds of particles, have been investigated by Fedorov, by Schönflies, and by Barlow, and it has been found that although there are no less than 230 different types of structure, they all possess the symmetry of one or other of the thirty-two classes of crystals.

Finally, therefore, according to this theory, a crystal may be regarded as a homogeneous assemblage of particles, constructed of interpenetrant space-lattices; and it is the space-lattice which determines its system and its angles and accounts for the law of rational indices.

[1] Of course the structure may be regarded in another way; opposite particles may be coupled together in pairs, R with L, so as to form a segment possessing a centre of symmetry, and this figure may be regarded as the basis of the structure; but even so it consists essentially of a right and a left half which are enantiomorphous.

In the next chapter it will be seen how the regular space-lattice structure of a crystal may be examined experimentally and the actual dimensions of the lattice measured.

One interesting property of a space-lattice may be mentioned here. All parallel planes are identically constructed and are equidistant, but amongst all the differently inclined sets of planes in the lattice some are more thickly beset with particles than others. It can be proved that the planes which are most thickly beset with particles are most widely separated from the adjoining parallel planes.

If, as might be expected, the faces of common occurrence upon a crystal are those in which the particles are most densely set, and the planes parallel to which the crystal cleaves are those which are least closely packed together, the fact that cleavage takes place only along certain planes, and generally parallel to the faces of common forms, will thus be explained.

If, as might also be expected, the particles of which isomorphous substances consist occupy nearly the same volume and possess the same symmetry, they may form parts of the same structure, and so give rise to mixed crystals. Again, if the structure be pseudosymmetric, so that one portion when turned round into a new position is only slightly changed, it may in like manner fit into or upon the other portion so as to constitute a continuous structure, and a mechanical explanation of the curious property of twinning is suggested.

CHAPTER II

THE INVESTIGATION OF CRYSTAL STRUCTURE BY MEANS OF X-RAYS

Previous to the year 1912 the theories as to the structure of crystals were based entirely on indirect evidence, derived from cleavage and the law of rational indices, from the homogeneity of crystals as shown by their physical properties, and from the correspondence between the symmetry of crystals and that of the space-lattices and regular point-systems.

Since that time, however, much new and direct evidence has been obtained through the discovery of the phenomena observed when a crystal is examined by means of X-rays.

1. **X-rays.**—These rays, which were discovered by Röntgen in 1896, are produced when the " cathode rays," which are sent out from the cathode in a vacuum tube, fall upon the glass wall of the tube or upon a specially provided metal " target " or " anticathode " placed in their path within the tube.

The quantity of X-rays emitted depends upon the material of the target, and is greatest when this is made of a heavy metal, such as platinum, iridium, or tungsten.

The X-rays travel outwards in all directions from their point of origin, in straight lines, and can penetrate through a greater or less thickness of solid matter, even when the material is opaque to light. The opacity of matter to the rays varies with its density, heavy substances, such as lead or barytes, being nearly opaque, while lighter substances, such as aluminium or wood, are comparatively transparent. The rays cause darkening in a photographic plate, and produce fluorescence in many substances; and when passed through a gas they cause " ionisation," which renders the gas a conductor of electricity.

The nature of these rays was for long uncertain, but has now been proved to be the same as that of light, though with a wave-length some 10,000 times shorter than that of light within the visible spectrum, and comparable with the distances between the atoms of a crystal.

An ordinary polished surface (as of glass), composed of atoms irregularly distributed, is rough and irregular in comparison with such minute waves, and consequently X-rays do not undergo regular reflection and refraction at such a surface, as do rays of light.

It is otherwise, however, with a crystal, in which the particles are arranged regularly in parallel planes, as in a space-lattice.

2. **Interference of X-rays.**—If a parallel beam of X-rays, of uniform wave-length, λ, be allowed to fall obliquely on a face of a crystal, *i.e.* on one of the planes of particles of the lattice, the action is somewhat analogous to that which takes place when a parallel beam of monochromatic light falls similarly upon a thin plate or film, as described on p. 134.

Let XX, Fig. 417, represent the plane of particles forming the face of the crystal, and Y, Z, etc., the successive planes of the lattice, parallel to XX and separated from one another by equal distances, d; and let AB, CD represent a parallel beam of X-rays, falling obliquely on XX at an angle θ. The incident wave-front DE, falling on the particles along DB, will be partly reflected and will give rise to a reflected wave-front BF, and a reflected beam BG, DH, in accordance with Huygens' construction.

Owing to the open spacing of the particles in comparison with the

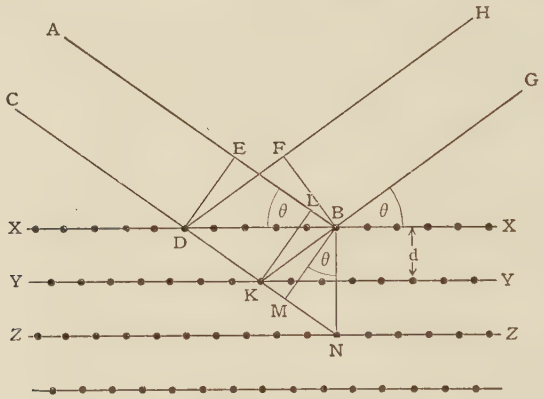


Fig. 417.—Reflection of X-rays by a Crystal.

wave-length, a considerable portion of the incident wave will pass through XX and encounter the particles in YY and succeeding planes within the crystal. These planes will each cause reflection of a part of the incident wave, and the reflected waves will all travel in the direction BG, and consequently will give rise to interference.

It will be seen from the figure (since KM = LB, and KN = KB) that the difference of path of the rays EBG and DKG is equal to $MN = BN \cdot \sin\theta = 2d \sin\theta$. The intensity of the beam which is reflected along BG will therefore depend upon the angle at which the rays meet the surface, and will be greatest when the difference of path is a whole number of wave-lengths, *i.e.* when $2d \sin\theta = n\lambda$, while if the difference is an odd number of half wave-lengths complete interference will take place.

It follows that the rays will not be reflected at any incidence whatever, but only when they are incident at or about certain definite angles, *viz.* when $\sin\theta = \frac{n\lambda}{2d}$. Owing to the fact that the rays penetrate some distance into the crystal and that a number of planes of particles contribute

to the reflected beam, a slight deviation from the angles of maximum reflection will cause a rapid decrease of intensity, and these angles will be sharply defined. For if the phase-difference between the rays reflected from two successive planes of particles be no more than (say) $\frac{1}{10}\lambda$, the rays from the first and sixth planes will differ by half a wave-length and will neutralise one another; and similarly those from the second and seventh, third and eighth, and so on; so that there will be no resultant reflection except when the incidence is such as to satisfy accurately the above equation.

3. **The X-ray Spectrometer.**—The values of the angle θ at which reflection takes place are determined by means of an instrument known as an X-ray spectrometer, the principle of which is shown in the diagram, Fig. 418.

The crystal C (say a cleavage-plate of rock-salt) is mounted on the axis of a spectrometer, whose divided circle is indicated at D, so that the planes of the lattice whose distances apart are to be measured are

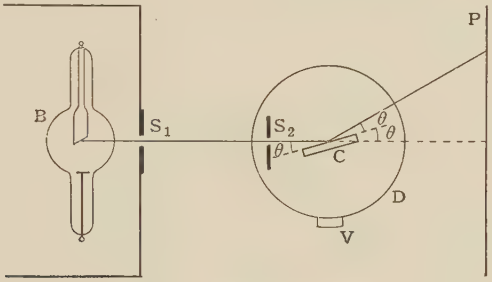


Fig. 418.—X-ray Spectrometer.

parallel to the axis, and a narrow beam of "monochromatic" X-rays from the bulb B, enclosed within a leaden box, is allowed to fall upon the crystal through slits in the leaden screens S_1 and S_2.

If the crystal be slowly rotated about the axis, the incident rays will be reflected only when it is inclined at angles which satisfy the above-mentioned equation; and if a photographic plate be placed behind the crystal, as at P, it will show on development a series of lines (at distances on either side of the central point proportional to tan 2θ), which represent the 1st, 2nd, 3rd, . . . order spectra of the X-rays, according as $2d \sin \theta = \lambda$, or 2λ, 3λ, . . . respectively.

Instead of a photographic plate being used to detect the reflected rays, advantage may be taken of the fact that a gas becomes a conductor of electricity, owing to "ionisation," when X-rays are passed through it, and that leakage consequently occurs in a charged condenser placed in the path of the rays. For this method an "ionisation-chamber" is attached to the spectrometer.

This consists of an insulated brass cylinder, closed at the ends with leaden plates and carried on a radial arm movable about the same axis as the crystal, like the telescope of an ordinary spectrometer. The tube

is filled with a gas which absorbs X-rays, such as sulphur dioxide, and contains an electrode insulated from the tube and connected to an electroscope. The rays reflected from the crystal are admitted to the chamber through a hole in the end-plate closed by a thin sheet of aluminium. The chamber being kept charged to a high potential, and the electroscope earthed and then insulated, leakage to the electrode occurs on the entrance of X-rays, which is thus indicated by a movement of the electroscope.

By setting the crystal and the chamber in positions corresponding to gradually increasing values of θ, and measuring the " ionisation-current " by observing the rate of movement of the electroscope, the angles at which maximum reflection takes place can be determined.[1]

4. **X-ray Spectra.**—By means of the X-ray spectrometer it has been found that the angles at which reflection occurs from a given plate of crystal are different when different metals are used for the anticathode

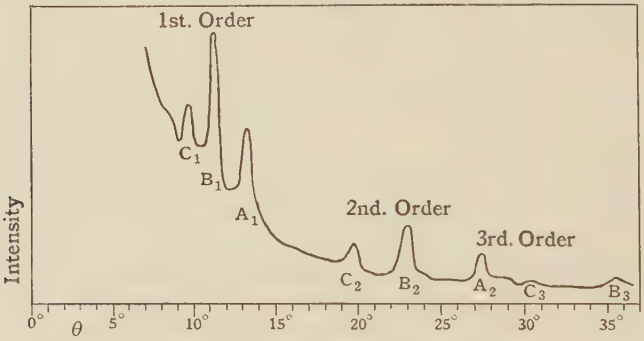


Fig. 419.—X-ray Spectra of Platinum.

from which the rays are derived. This may be explained as due to differences in the wave-length of the X-rays emitted by different substances.

It has been shown, by Moseley, that each element, when bombarded by the cathode rays, emits X-rays of definite wave-lengths, forming a characteristic X-ray spectrum, just as its vapour gives a characteristic luminous spectrum when heated.

The X-ray spectra of the elements are generally very much simpler than their light-spectra, and consist of only a few lines ; and the wave-lengths of these have been found to have a very simple connection with the position of the element in the periodic table, *i.e.* its " atomic number " (*cf.* p. 225), the wave-length diminishing as this number increases.

The spectrum from a platinum anticathode, given by reflection from a cube-plane of rock-salt, is shown in Fig. 419, in which the abscissae give the values of the angle θ (which for small angles is roughly proportional to its sine, and therefore to the wave-length), and the ordinates represent the intensity of the rays, as measured by the ionisation-current.

It will be seen from the figure that there are three well-marked lines,

[1] This method is due to Sir Wm. Bragg and W. L. Bragg, to whose book, *X-rays and Crystal Structure*, reference may be made for a further account of this subject.

A, B, C, forming the characteristic platinum spectrum, which are recognisable in the 1st, 2nd, and 3rd order spectra, and that between these lines there is a considerable amount of radiation corresponding to the continuous spectrum of white light.

For the investigation of crystal structure by the X-ray spectrometer the nearly monochromatic radiation of the characteristic rays is required, while for other purposes the " white " radiation of the continuous spectrum is needed (see p. 298).

5. **Analysis of Crystal Structure.**—The values of the angle θ, at which maximum reflection of a given radiation occurs, having been determined by means of the X-ray spectrometer, the distance d between the successive planes of particles can be found, in terms of the wave-length, from the relation: $d = \frac{n\lambda}{2 \sin \theta}$.

If the reflections from planes of particles having different directions in the lattice be successively examined—as, for example, in an orthorhombic crystal, those from the planes parallel to the faces (100), (010), (001)—the relative distances apart of the corresponding sets of planes may be found, and hence the structure of the lattice determined.

If the wave-length of the radiation be known, the actual distances between the planes may be measured (see p. 289).

It must be borne in mind that, owing to the open structure of a crystal as compared with the wave-length of X-rays, the reflection is produced by a number of layers of particles within the crystal, and not by the surface (as in the case of light), so that the external shape of the crystal or fragment used is immaterial.

6. **Cubic Crystals.**—In a simple cubic lattice, like Fig. 410 (i), p. 274, if the distance d_{100} between two successive planes of particles parallel to a cube-face be a (Fig. 420), the corresponding distance d_{110} between planes (through AE, BDHF, CG, etc.) parallel to a face of the dodecahedron will

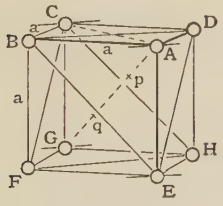


Fig. 420.—Cubic Lattice.

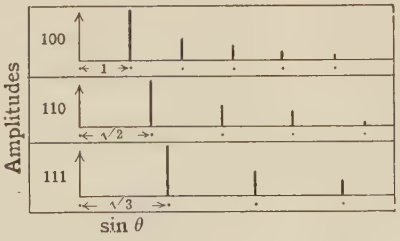


Fig. 421.—Spectra from Cubic Lattice.

be $\frac{\sqrt{2} \cdot a}{2}$, and the distance d_{111} between the planes (through A, BDE, CFH, G, etc.) parallel to a face of the octahedron, *viz.* Ap, pq, qG, etc., will be $\frac{\sqrt{3} \cdot a}{3}$. Hence the sines of the angles θ_{100}, θ_{110}, θ_{111}, for the first order spectra of a given monochromatic radiation reflected from these

planes will be in the proportion of $\frac{1}{d_{100}} : \frac{1}{d_{110}} : \frac{1}{d_{111}} = 1 : \sqrt{2} : \sqrt{3}$, and the complete series of reflections will be as shown in the diagram, Fig. 421, in which the thick vertical lines represent the reflections of successive orders from the several planes, the abscissae being taken proportional to $\sin\theta$, while the heights of the lines represent the wave-amplitudes of the reflected rays and indicate their relative intensities,[1] which diminish rapidly in the successive orders.

If the lattice be the centred-cubic (Fig. 422), and the distance d_{100} between successive cube-planes (through ABFE, K, DCGH, etc.) be

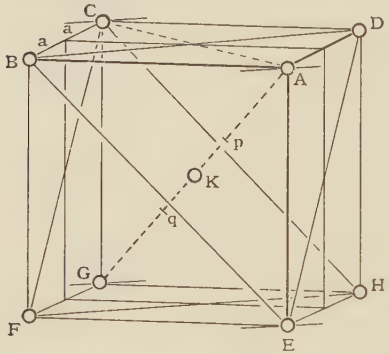


Fig. 422.—Centred Cubic Lattice.

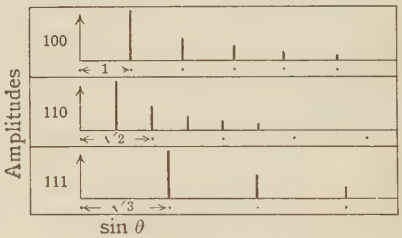


Fig. 423.—Spectra from Centred Cubic Lattice.

represented by a, then the distance, d_{110}, between the planes through AE, BDHFK, CG, etc., will be $\sqrt{2} \cdot a$, and the distance d_{111} will be that between the plane BDE, or CHF, and the parallel plane through K, *viz.* Kp or $Kq = \frac{AG}{6} = \frac{\sqrt{3} \cdot a}{3}$. The sines of the angles of the first reflections will then be in the proportion—

$$\sin\theta_{100} : \sin\theta_{110} : \sin\theta_{111} = \frac{1}{d_{100}} : \frac{1}{d_{110}} : \frac{1}{d_{111}} = 1 : \frac{\sqrt{2}}{2} : \sqrt{3},$$

as shown in the diagram, Fig. 423.

Lastly, if the lattice be the cube with centred faces (Fig. 424), and the distance d_{100} between successive planes (through ABFE, MJNL, DCGH, etc.) be again a, then the distance d_{110} (between the planes through AE, IL, BMDHNF, JK, CG, etc.) will be $\frac{AC}{4} = \frac{\sqrt{2} \cdot a}{2}$; and the distance d_{111} (between the planes through A, BMDLEI, CKHNFJ, G, etc.) will be $\frac{AG}{3} = \frac{\sqrt{3} \cdot 2a}{3}$. The sines of the angles θ for the first reflections will then be in the proportion—

$$\sin\theta_{100} : \sin\theta_{110} : \sin\theta_{111} = \frac{1}{d_{100}} : \frac{1}{d_{110}} : \frac{1}{d_{111}} = 1 : \sqrt{2} : \frac{\sqrt{3}}{2},$$

as shown in the diagram, Fig. 425.

[1] The intensity being proportional to the square of the amplitude.

Thus by comparing the spectra obtained from the cube-, dodecahedron-, and octahedron-planes, the three types of cubic lattices may be distinguished.

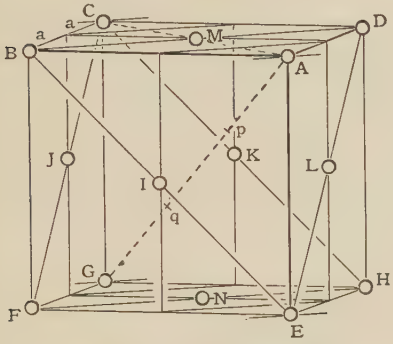


Fig. 424.—Cube with Centred Faces.

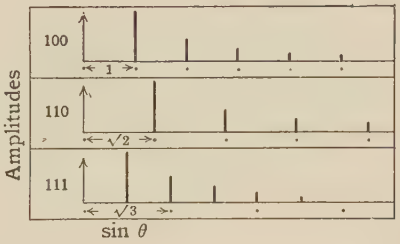


Fig. 425.—Spectra from Cubic Lattice with Centred Faces.

7. **Structure of Rock-salt and Sylvite.**—Among the first crystals to be examined with the X-ray spectrometer were those of rock-salt and sylvite, which are isomorphous and resemble one another in their cubic cleavage, and may be expected to be similar also in structure.

The spectra given by the several planes of sylvite were found to have

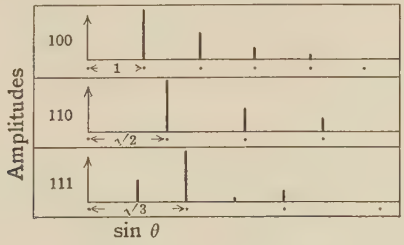


Fig. 426.—Spectra from Rock-salt.

the relative positions and intensities shown in Fig. 421, which corresponds to a simple cubic lattice. But in the case of rock-salt, while the spectra from the cube- and dodecahedron-planes were similar to those from the corresponding planes of sylvite (though placed at slightly larger angles indicating a slightly closer lattice) and showed the same regular decrease in intensity, the series of spectra from the octahedron-face was of a different type, the second order being more intense than the first, as shown in Fig. 426.

If the particles forming the planes of the lattice were molecules, KCl and NaCl, the spectra given by similar lattices formed of such particles should be of the same type. The divergence of the octahedron-spectra given by rock-salt from the normal type suggested that the reflecting

particles might be *atoms*, and that the structure of the crystals might be that shown in Fig. 427.

Here the metal atoms (●) and the chlorine atoms (○) each form a face-centred cubic lattice (ABCD . . . N and OPQR . . . Y), and the two lattices interpenetrate so that the chlorine atoms lie at the middle points of the cube-edges of the metal lattice, and *vice versa*.

In such a structure the planes (100) are all similarly beset with metal atoms and chlorine atoms in equal numbers; and the distances apart of these planes, as indicated by the spectra, will be the same as those in either of the two constituent face-centred lattices, *viz.* OM. The same is true of the planes (110), which are spaced at distances equal to A*s*.

It is otherwise, however, with the octahedron-planes, which contain either only metal atoms (as MIL) or only chlorine atoms (as OX′ Y′), the two kinds of planes being arranged alternately, at equal distances.

Were one set of atoms, say those of chlorine, alone present, their

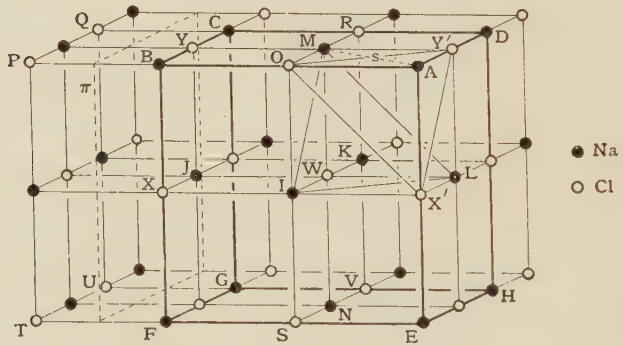


Fig. 427.—Structure of Rock-salt.

face-centred lattice would give spectra from its cube-, dodecahedron-, and octahedron-planes at angles whose sines were in the proportion $1 : \sqrt{2} : \frac{\sqrt{3}}{2}$ (Fig. 425). If, now, the other set of atoms were inserted, the distances between adjacent cube-planes, and those between adjacent dodecahedron-planes of the structure, and consequently the angles of the corresponding spectra, would be unchanged; but the distances between the octahedron-planes would be halved, a plane of metal atoms being placed midway between every pair of chlorine planes. At the angle corresponding to the first spectrum the rays reflected from the inserted (metal) planes will differ in phase by half a wave-length from those reflected from the chlorine planes, and if the reflecting power of the two kinds of planes is equal will neutralise them by interference. If the reflecting power of the inserted planes is less, the reflected rays will be partially neutralised and their intensity diminished.

The first spectrum from the face-centred lattice will thus be either cut out altogether or diminished in strength, and the same will hold for the

third spectrum and other spectra of odd orders, while the spectra of even orders will be strengthened.

The reflecting power of a plane of atoms may be expected to depend upon its mass per unit area, *i.e.* upon the number of atoms per unit area and their atomic weight.

Now in the case of sylvite the atomic weights of chlorine (35·2) and potassium (38·8) are so nearly equal that the two sets of octahedron-planes, consisting of chlorine atoms and potassium atoms respectively, will on the above assumption be nearly equal in reflecting power, so that the first and third spectra from the face-centred lattice will be practically cut out, while the even spectra will be strengthened. Hence the angles of the spectra from the several planes will correspond to the proportion $1 : \sqrt{2} : \sqrt{3}$; or, in other words, the structure described will give spectra like those of a simple cubic lattice, as actually observed with sylvite.

In the case of the octahedron-planes of rock-salt (Na = 22·8) the reflecting power of the sodium planes will be less than that of the chlorine planes, and the first and third spectra will be weakened, but not extinguished, as is found to be the case (Fig. 426).

The spectra given by rock-salt and sylvite are thus satisfactorily explained, and indicate that in these crystals the reflecting particles are the constituent atoms.

8. **Absolute Measurement of Atomic Distances.**—The structure of a cubic crystal such as rock-salt having been established, it becomes possible to determine the absolute distances between the planes of atoms, and hence also the wave-length of the X-rays.

Thus, if d be the distance between two adjacent cube-planes of the structure (see Fig. 427), the volume of the small cube AOMWL . . . will be d^3, and its mass will be $d^3\rho$, where ρ is the density of the crystal. Each small cube will contain half a molecule NaCl (*i.e.* one-eighth of each of the four atoms of sodium placed at its corners, and a corresponding amount of chlorine); and if M be the molecular weight (referred to the hydrogen atom as unity), and the mass of an atom of hydrogen be m, the mass of the small cube will be $\frac{M}{2} . m$. Hence $d^3\rho = \frac{M}{2} . m$, and $d = \sqrt[3]{\frac{M . m}{2\rho}}$.

In the case of rock-salt, M = 58·0, ρ = 2·17; and since $m = 1{\cdot}662 \times 10^{-24}$ gram, we have—

$$d = 2{\cdot}81 \times 10^{-8} \text{ cm.}$$

When d is thus known the wave-length of the X-rays used may be determined.

Thus, if a platinum anticathode be used, the principal line (B) of the first spectrum (see Fig. 419) given by the cube-face of rock-salt occurs at an angle $\theta = 11° 33'$; hence the wave-length of the rays from platinum corresponding to this line is—

$$\lambda = 2d . \sin 11° 33' = 1{\cdot}126 \times 10^{-8} \text{ cm.}$$

The wave-length of any given rays being thus found, these rays may be used to measure the distances between the planes of any other crystals.

9. **Structure of Blende and of Diamond.**—Crystals of blende, though

they also belong to the cubic system, reveal a type of structure different from that of rock-salt.

The spectra given by the cube-, dodecahedron-, and octahedron-planes of blende are shown in Fig. 428.

The angles of the first order spectra from the three planes indicate a face-centred lattice, as in the case of rock-salt; but the structures of the two crystals cannot be similar, since in blende only the spectra from the dodecahedron-planes show the normal decrease of intensity in successive orders.

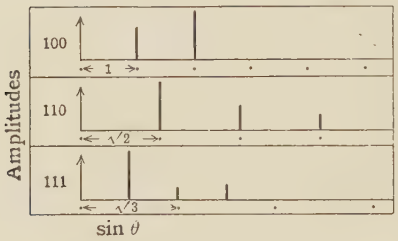


Fig. 428.—Spectra from Blende.

If the (heavier) zinc atoms be supposed to form a face-centred lattice, the sulphur atoms must be so placed that the dodecahedron-planes contain both zinc and sulphur atoms and are all similar to one another, but that the cube-planes, and also the octahedron-planes, consist alternately of zinc and sulphur, and are so placed as to give, by interference, the observed intensities of the spectra.

These conditions are fulfilled by the structure shown in Fig. 429, in

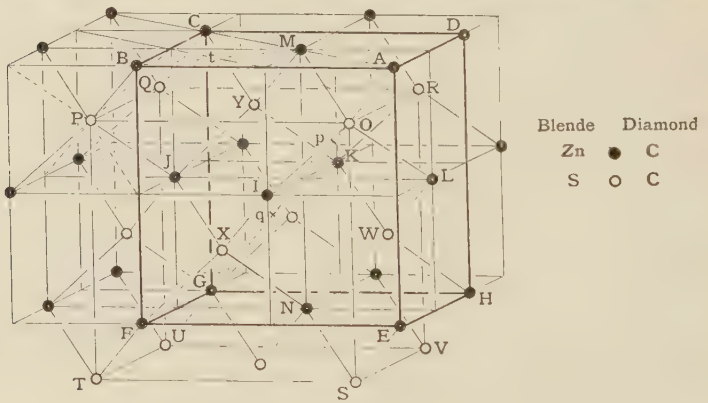


Fig. 429.—Structure of Blende and of Diamond.

which the zinc atoms and the sulphur atoms form the face-centred cubic lattices ABCD . . . N and OPQR . . . Y respectively, and each atom of one kind is separated from one of the other kind by a distance equal to AO or one-quarter of the diagonal AG of the cube ABCD . . . H; so that if one lattice were moved relatively to the other through this distance along one of the cube-diagonals the two lattices would coincide. The sulphur atoms thus occupy the centres of one-half of the small cubes, such as AMIL, into which the zinc lattice may be divided, and *vice versa*.

In this structure the dodecahedron-planes, such as EAOMYCG, are all alike, containing equal numbers of atoms of zinc and sulphur, and are

spaced at uniform distances, equal to Mt. Hence the spectra from these planes will show the normal decrease of intensity.

The cube-planes, on the other hand, consist alternately of zinc atoms only (as ADHE) and of sulphur atoms only (as ORVS), the sulphur planes being placed midway between the zinc planes. The result will be a weakening of the first and third spectra which would be given by the zinc planes alone, and a strengthening of the second spectrum, as in the case of the octahedron-planes of rock-salt.

The octahedron-planes also consist alternately of zinc and sulphur; but here the planes are not at equal distances, each sulphur plane being nearer to the zinc plane on one side of it than to that on the other side in the proportion of 1 : 3; so that, if d be the distance between two adjacent zinc planes, the intermediate sulphur plane lies at distances $\frac{d}{4}$ from one plane and $\frac{3d}{4}$ from the other.[1]

In the first spectrum the rays reflected from the sulphur planes will differ in phase from those from the zinc planes by one quarter of a wave-length, and this difference will cause no weakening of the reflection.

But in the second spectrum the difference of phase will be half a wave-length, and this spectrum will be weakened to an extent depending on the difference of the atomic weights of zinc and sulphur.

These results agree with the observed spectra of Fig. 428 and indicate that blende has the structure shown in Fig. 429. Every atom of zinc is here at the centre of a tetrahedron formed of four sulphur atoms, and *vice versa* (*cf.* Fig. 508, p. 371).

The structure of diamond is similar to that of blende, in that it consists of two face-centred cubic lattices interpenetrating in the same manner (Fig. 429), but the two lattices are formed of similar atoms, *i.e.* of carbon, so that their planes have equal reflecting power, and consequently those spectra which in blende are weakened by interference are here entirely cut out, *viz.* the first and third spectra from the cube-planes and the second spectrum from the octahedron-planes.

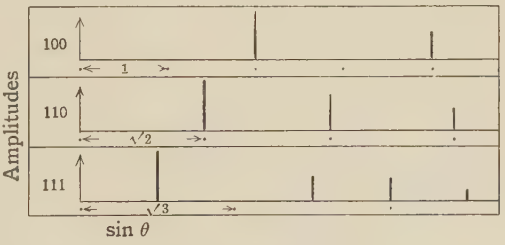


Fig. 430.—Spectra from Diamond.

The spectra given by diamond are shown in Fig. 430. The angles at which they occur are greater than the corresponding angles in blende, owing to the closer spacing of the atoms in diamond. (In blende

[1] In the face-centred lattice formed by the zinc atoms the distances (d) between the octahedron-planes, such as BDE, CHF, which pass through p and q on the cube-diagonal AG, are equal to one-third the length of this diagonal, *i.e.* $Ap = pq = qG$ (*cf.* Fig. 424): the sulphur atoms lie on the same diagonal (as at O, U) at a distance $AO = GU = \frac{AG}{4}$ from a zinc atom. Hence, if $AG = 1$, $Ap = \frac{4}{1\sqrt{2}} = d$, $AO = \frac{3}{1\sqrt{2}}$, $Op = \frac{1}{1\sqrt{2}}$

$d_{100} = 2{\cdot}7 \times 10^{-8}$ cm.; the corresponding distance ($2d_{100}$) in diamond $= 1{\cdot}78 \times 10^{-8}$ cm.)

In diamond each carbon atom of one lattice (○) is surrounded by four similar atoms of the other lattice (●), arranged in a tetrahedral manner, and *vice versa*, as indicated in Fig. 429 (*cf.* also Figs. 482, 508).

10. **Homogeneity of Crystal Structures: Unit Cell.**—Every crystal, like each of the space-lattices, if supposed to be infinitely extended in all directions (so as to eliminate its boundaries), may be considered as a homogeneous structure consisting of an infinite number of precisely similar parallelepipedal units or cells, stacked together in parallel positions as in Haüy's theory, from any one of which the complete structure can be obtained by successive equal movements of translation in the directions of the edges of the cell.

The atoms of the substance are distributed about each such cell, either at the corners or on the faces or within the cell, in the proportions (if the substance be a compound) corresponding to the chemical composition and in positions consistent with the symmetry of the crystal.

In the case of rock-salt and sylvite, having the structure shown in Fig. 427, the unit cell has the dimensions of the cube ABCD . . . H (consisting of eight of the small cubes AOMY′ . . . L, etc.).[1]

In this cube the six atoms (M, I, L, etc.) at the centres of its faces lie half within the cell and half in an adjoining cell, and together contribute three atoms to the contents of the cell. These atoms are all of one kind (say sodium). The eight atoms, of the same kind, at the corners, each have one-eighth within the cell and together contribute one atom, making four atoms, in all, of sodium. The atoms of the other kind (chlorine) lie on the edges and at the centre of the cell. The twelve former together contribute three atoms, and these make with the central atom four atoms, in all, of chlorine. The unit cell contains, therefore, 4NaCl (or 4KCl).

In blende the unit cell is the cube ABCD . . . H of Fig. 429, and contains, in all, four atoms of zinc situated at its corners and the centres of its faces, and four atoms of sulphur situated within the cell at the points OYXW upon its four diagonals. The unit cell thus contains 4ZnS.

In diamond, since the structure is the same as that of blende, but with carbon replacing both zinc and sulphur, the unit is the corresponding cube and contains eight atoms of carbon. The distance apart (d_{100}) of two adjacent similar cube-planes (as indicated by the angle of the first spectrum) is here one *quarter* of the side of the unit cell, corresponding to the distance between a zinc plane and a sulphur plane in blende; hence the edge of the unit cube in diamond will be $4d_{100}$.

When the dimensions of the unit cell and the arrangement of the atoms therein have been determined from the angles of the spectra and their intensities, the correctness of the result may be tested by comparing the dimensions so found with those calculated from the density as explained in Art. 8.

[1] Any parallel cube of the same dimensions would contain the same number of atoms and might be considered as the unit cell of the structure.

Thus, for blende we have—

	Edge of Unit Cell
From spectra . . .	$2l_{100} = 5{\cdot}39 \times 10^{-8}$ cm.
„ density . . .	$2d_{100} = \sqrt[3]{\frac{4M \,.\, m}{\rho}}$
	$= 5{\cdot}41 \times 10^{-8}$ cm.

$[M = 96{\cdot}7,\ \rho = 4{\cdot}06]$

Similarly, for diamond—

	Edge of Unit Cell
From spectra . . .	$4l_{100} = 3{\cdot}55 \times 10^{-8}$ cm.
„ density . . .	$4l_{100} = \sqrt[3]{\frac{8C \,.\, m}{\rho}}$
	$= 3{\cdot}56 \times 10^{-8}$ cm.

$[C = 11{\cdot}91,\ \rho = 3{\cdot}52]$

11. **Structure of Fluor.** Another mineral whose structure is related to that of blende and diamond is fluor, CaF_2. The calcium atoms form a face-centred cubic lattice, as do the zinc atoms in blende, while the fluorine atoms, which are twice as numerous, form two similar face-centred cubic lattices, each corresponding to that of the sulphur atoms in blende, and occupy the centres of *each* of the eight small cubes of which the unit cell (containing $4CaF_2$) is composed (*cf.* Fig. 429). The spectra are practically identical in arrangement with those given by diamond.

The reflecting planes parallel to (110) are equidistant and all alike, containing both calcium and fluorine atoms in the proportion of 1 : 2; those parallel to (100) are also equidistant but contain alternately calcium atoms and fluorine atoms only, the fluorine planes being twice as thickly set with atoms as the calcium planes. The octahedral planes also contain atoms of one kind only, but they are not equidistant: on either side of each such plane of calcium atoms, at a distance equal to one-quarter of that between two adjacent calcium planes, is a plane containing an equal number of fluorine atoms. Here, as in the octahedron-planes of blende or diamond, the rays reflected from the two kinds of planes will differ in phase by $\frac{\lambda}{4}$ in the first, and by $\frac{\lambda}{2}$ in the second spectrum; and the latter will therefore be weakened, or entirely destroyed according to the relative reflecting power of the two kinds of planes.

The fact that here, as in diamond, the second spectrum from (111) and the first spectrum from (100) are entirely absent indicates that the reflecting power of a plane of calcium atoms is the same as that of a plane containing twice the number of fluorine atoms, or as that of two (suitably placed) planes having the same number of such atoms, per unit area, just as in sylvite the reflecting power of similar planes of potassium and chlorine atoms is the same. Since the atomic weight of Ca(=39·8) is approximately twice that of F(=18·9), while the atomic weights of K(=38·8) and Cl(=35·2) are nearly equal, it would appear that the reflecting powers of planes of atoms are approximately proportional to their mass per unit area.

12. **Structure of Pyrites.** -The structure of pyrites is somewhat more complex, and is shown in Fig. 431.

The iron atoms form a face-centred cubic lattice, and one atom of sulphur is situated in each of the eight small cubes which make up the unit cell, as are the fluorine atoms in fluor; but these atoms are not in the centres of the cubes, as in fluor, but lie out of the centre, on one of the diagonals. The diagonals on which the atoms in adjacent small cubes lie are not parallel, and are placed as shown in the figure. They form four sets of continuous diagonal lines, which traverse the structure but nowhere intersect one another. In each small cube the diagonal passes through one of the iron atoms and the opposite empty corner of the cube, and the sulphur atom is situated upon the diagonal so that its distances from the empty corner and from the iron atom are approximately in the

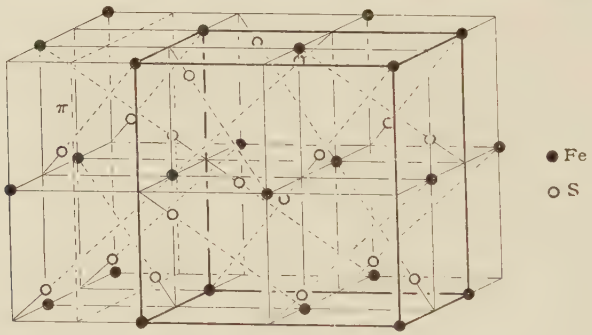


Fig. 431.—Structure of Pyrites.

proportion of 1 : 4. Hence in the structure as a whole the sulphur atoms are arranged in pairs about the empty corners of the small cubes.

13. **Symmetry of Crystal Structures.** The structures above described will be seen to possess certain planes and axes of symmetry, and in most cases to be centro-symmetrical. Thus, the rock-salt structure of Fig. 427 is symmetrical about the planes which pass through its atoms and are parallel to a face of the cube or of the dodecahedron. Any line of atoms parallel to a cube-edge is a fourfold axis, any such line along a cube-diagonal is a threefold axis, and any such line along a diagonal of a cube-face a twofold axis. Moreover, every atom is situated at a centre of symmetry, and there is a centre of symmetry also at the centre of each face of any of the small cubes. Thus, the rock-salt structure has the symmetry of the holosymmetric class of the cubic system.

It will be seen, further, that the structure is also similar on either side of a cube-plane (such as π) situated midway between two planes of atoms, though it will not be brought into coincidence with itself by a simple reflection in this plane: the reflection must be accompanied by a movement of translation through the distance BY or BX, parallel to the plane. The combined operation will bring (for example) P to B and thence to Y or X. Such a plane is called a "plane of gliding symmetry."

Similarly, the rock-salt structure can also be brought to coincide with itself by a quarter-turn about an axis, parallel to a cube-edge, through a point (such as s) in the middle of a face of any of the small cubes, combined with a translation along the axis through the length of a cube-edge. Thus the atom at A will be transferred to O, and thence to I. Such an axis is called a " screw-axis of symmetry " (here, of fourfold symmetry).

In rock-salt planes of both ordinary and gliding symmetry are present ; but in some crystals such as pyrites there are no ordinary planes but only planes of gliding symmetry (parallel to the cube-faces) as at π ; nevertheless, since the translation involved in a plane of gliding symmetry does not exceed the minute distance between neighbouring atoms, a crystal whose structure possesses such planes of symmetry is indistinguishable from one having an ordinary plane of symmetry.

For a similar reason, if the structure of a crystal possesses screw-axes of symmetry, its form will be symmetrical about ordinary symmetry-axes in the corresponding directions.

Two other structures only need be considered here—those of calcite and of cuprite.

14. **Structure of Calcite.**—The arrangement of the calcium and carbon atoms in calcite is somewhat similar to that of the sodium and chlorine

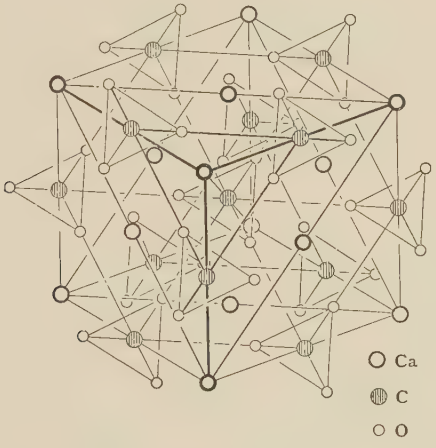


Fig. 432.—Structure of Calcite.

atoms in rock-salt, and may best be understood by supposing the unit cube of salt to be compressed along one of its diagonals until it has the form of the cleavage-rhombohedron of calcite, as in Fig. 432, and the sodium and chlorine atoms to be replaced by calcium and carbon atoms respectively. The rhombohedron-planes then contain calcium and carbon atoms in equal numbers, while planes parallel to (111) consist alternately of calcium atoms and of carbon atoms alone, arranged in a triangular pattern like that of Fig. 412. The oxygen atoms lie in the same horizontal planes as the carbon atoms, about each of which they form

a group of three arranged in an equilateral triangle. The sides of these triangles are not parallel to those of the main triangular pattern, but at right angles to them, as shown in the figure. In each horizontal plane they are all parallel, but in successive planes they point in opposite directions.

Thus the vertical planes through the rhombohedron-edges are planes of gliding symmetry, the movement of translation being equal to half the shorter diagonal of the rhombohedron-face. The structure also possesses the vertical trigonal axis, the three horizontal digonal axes, and the centre of symmetry proper to the calcite class (dihexagonal alternating).

In dolomite the structure is similar, but the horizontal metal planes are formed alternately of calcium and of magnesium atoms. The horizontal symmetry-axes and the planes of gliding symmetry of calcite are thus eliminated, and the symmetry is *hexagonal* alternating.

The structure of sodium nitrate, which forms parallel growths on calcite (p. 266), is exactly analogous to that of calcite, N taking the place of C, and Na that of Ca. Moreover, the dimensions of the two structures are almost identical.

15. **Structure of Cuprite.**—In cuprite, Cu_2O, the copper atoms form a

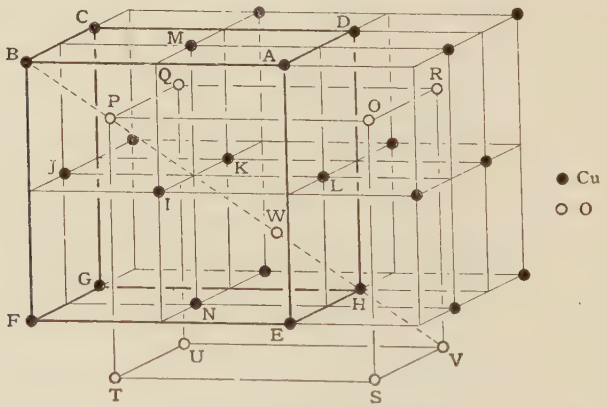


Fig. 433.—Structure of Cuprite.

face-centred cubic lattice, ABCD . . . N, and the oxygen atoms a centred cubic lattice, OPQR . . . W, of the same size ; and the structure may be regarded as a face-centred lattice composed of copper atoms with an atom of oxygen in the centres (P, W) of *two* of the small cubes which lie on one of its diagonals (Fig. 433).

This structure is holosymmetric. The crystals, however, have been shown by their form (p. 55) to belong to the holoaxial class of the cubic system, and thus have a lower type of symmetry than that shown by the structure. A similar apparent discrepancy between the symmetry of a crystal and that of its structure is shown also by salt and sylvite (p. 288), and possibly also by diamond. It has been attributed either to a want of

symmetry in the constituent atoms or to a slight deviation, too small to be recognised, of the structure from its apparent symmetry; but the explanation is uncertain.

16. **The Laue Diffraction Pattern.** Before the development of the spectrometer-method, which has so far been considered, and which is due to Sir W. Bragg, the discovery had been made by Laue, Friedrich, and Knipping, in 1912, that when a narrow beam of X-rays is allowed to traverse a plate of crystal and to fall upon a photographic plate, in addition to a central spot due to the direct beam a number of other spots are produced on the plate, forming a pattern which depends upon the nature of the crystal used and the direction in which it is traversed by the rays.

This discovery was the result of the proposal, due to Laue, to use the regular structure of a crystal as a grating, of extreme fineness, which might show diffraction phenomena with X-rays, comparable with those produced with light by an ordinary diffraction grating, on the assumption

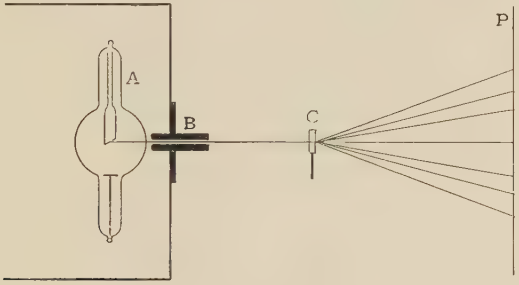


Fig. 434.—The Laue Method.

(not then proved) that X-rays, like light, were a vibration of the ether, but of too short a wave-length to be affected by ordinary gratings.

The experiment was made by Friedrich and Knipping with the apparatus shown in the diagram, Fig. 434. A narrow beam of X-rays from the bulb A, transmitted through a small hole in the block of lead, B, in the lead screen surrounding the bulb, meets the plate of crystal C, behind which is placed a photographic plate P. The crystal is mounted on an adjusting apparatus like that used on a goniometer, so that its inclination to the incident rays may be varied.

The pattern produced by a plate of blende parallel to (111) is shown in Fig. 435. The central spot marks the incidence of the direct X-ray beam, while each of the other spots in the pattern is due to a separate oblique beam deflected by the crystal.

The theory of the formation of the pattern, as the result of the diffraction of very short waves by an assemblage of particles arranged regularly in three dimensions (after the manner of a space lattice), was completely worked out by Laue; and the nature of X-rays as consisting of a wave-motion was thus first satisfactorily established.

It was shown later, by W. L. Bragg, that the positions of the spots

in the Laue pattern were those which would be given by the reflection of the incident beam, in the manner already explained (see Fig. 417), by planes of particles inclined to it at different angles within the crystal,

Fig. 425.—Laue Diffraction Pattern; Blende (111).

as in Fig. 436, which represents an orthorhombic crystal viewed along the axis X. If the X-rays were "monochromatic," of wave-length λ, reflection would only take place at those planes whose inclination and

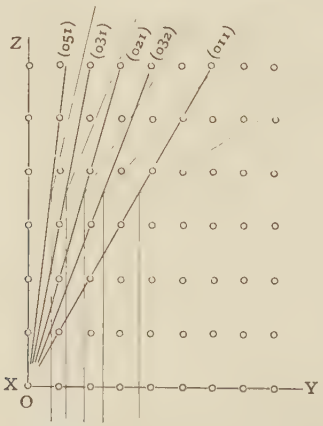


Fig. 436.—Formation of the Laue Pattern.

distance apart were such as to satisfy the condition $2d \sin\theta = n\lambda$. For the Laue method, therefore, X-rays of various wave-lengths are required, corresponding to the continuous spectrum in Fig. 419. From this "white"

radiation any given set of planes will reflect rays of such a wave-length that the above condition is satisfied. Thus, if a Laue pattern could be formed by rays from the visible spectrum, the several spots would be seen to be of different colours, corresponding to the wave-lengths reflected.

If the incident beam is parallel to an axis of symmetry, or lies in a plane of symmetry of the crystal, the reflecting planes of particles will be symmetrically arranged about this axis or plane, and the spots of the Laue pattern will therefore also be symmetrically placed. In Fig. 435 the incident beam is parallel to an axis of di-trigonal symmetry, and this symmetry is clearly visible in the pattern.

BOOK V

THE DESCRIPTION AND DETERMINATION OF MINERALS

CHAPTER I

DESCRIPTIVE TERMS

It has been shown in Book III how, owing to isomorphous and other intermixtures, a mineral species may possess very variable characters, but that these characters vary together in a regular and uniform manner.

We have now to see how different specimens of one and the same mineral may present many irregular varieties of aspect, even when they are identical in their form and crystallophysical properties, in their specific gravity and chemical composition.

These varieties of aspect are chiefly due to the different ways in which minerals may be aggregated, and to the great variety of colour which they present, not only as isomorphous mixtures, but also owing to the enclosure of impurities.

Before the study of the essential properties was developed the external aspect, and what may now be called the " inessential " characters, were mainly relied upon by the " natural-history " school for the discrimination of species (see p. 221). Minerals were mainly distinguished not only by their crystalline form, but also by such characters as colour, lustre, hardness, fusibility, and the form and structure of their aggregates ; consequently a great number of species- and variety-names were given, on account of differences in these inessential characters, and different names were given to minerals which we should now refer to the same species.

These characters and the names relating to them are still largely used by mineralogists ; among them the hardness, the streak, and the lustre are of considerable value in the practical determination of minerals ; the remainder are chiefly useful in the description of specimens.

1. **Morphological and Structural Characters :—Habit.**—Although every mineral which crystallises has only one characteristic crystalline form, yet any crystal may assume various shapes, due to a more rapid growth in one direction than another. A cube of sodium chlorate, for example, crystallising on the bottom of a beaker will tend to grow more rapidly in a lateral than in a vertical direction, since its under-surface is protected from contact with the solution, and it therefore becomes a square tablet, whereas if suspended within the solution it would grow evenly and remain a cube. The shape which the crystal presents to the eye is called its " habit," and the habit depends, not only on the nature of the substance, but also on the conditions which have prevailed during its growth. It is

therefore not a constant, but a variable character. A crystal of albite may have either of the two forms of Figs. 437 and 438, but the *angles* between corresponding faces are the same in both (*cf.* p. 11).

The following varieties of habit are distinguished by mineralogists :

Tabular.—When one pair of parallel faces is much larger than the others the mineral is said to crystallise in "tables" or "plates," *e.g.* barytes from Westmorland (Fig. 439).

Pyramidal.—When the predominant faces meet in an apex, or in a

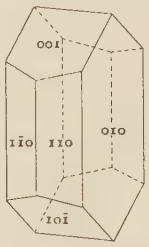


Fig. 437.—Albite.

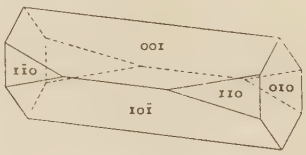


Fig. 438.—Albite, "Peridine"-habit.

pair of opposite apices, the mineral is said to crystallise in "pyramids" or "bipyramids." Different pyramids are distinguished by the form of their base. Anatase shows a bipyramid with square base (Fig. 124); sulphur, one with rhombic base (Fig. 148); quartz, one with hexagonal

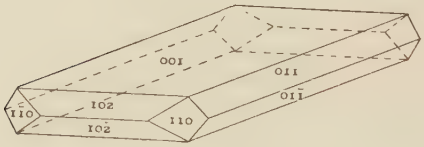


Fig. 439.—Tabular Barytes.

Fig. 440.—Barytes from Hungary.

base (Fig. 162). Witherite is pseudo-hexagonal, and also forms pyramids with an apparently hexagonal base.

Prismatic.—When the crystal is elongated in one direction the mineral is said to crystallise in "prisms," *e.g.* tourmaline, which almost always has a prismatic habit. When a prismatic crystal is bounded at one end by crystal-faces it is said to be "terminated"; if at both ends it is said to be "doubly terminated." Many minerals, such as quartz, generally spring from the sides of a vein or cavity, to which they are attached by one end; hence doubly terminated crystals of such minerals are comparatively rare.

Acicular.—When the crystals are long and very thin the mineral is said to be "acicular," or to crystallise in "needles," *e.g.* scolecite from Bombay, or cerussite from Cornwall (Fig. 441).

Capillary.—When the crystals are so thin as to be like fine threads or hairs they are said to be "capillary," *e.g.* millerite from Merthyr-Tydvil.

The above characters depend only on the relative dimensions of the faces. They are not essential, because the same mineral may occur in one place in crystals of one habit, at another place in crystals of quite a different habit. Thus barytes generally occurs in tabular crystals (Fig. 439), but that from Betler in Hungary is found in prisms which have such a different aspect (Fig. 440) that they were originally described as a new mineral under the name "wolnyn."

Cuprite often crystallises in very perfect cubes, but it is also found in

Fig. 441.—Acicular Cerussite.

capillary crystals, which are really elongated cubes, but which were once regarded as a distinct variety, and received the name of "chalcotrichite."

The appearance of the crystals of a mineral also depends upon their mode of occurrence or formation. Thus, crystals which have been formed in a liquid or plastic medium may be bounded on all sides by plane faces, as in the gypsum crystals (Fig. 235, p. 98) found embedded in many clays, or the orthoclase crystals occurring in many granitic rocks. In igneous rocks large crystals of this kind, embedded in a finer grained mass, are described as *porphyritic*, from the resemblance of the structure to that of "porphyry," a fine-grained purple or greenish rock containing white crystals of felspar. Some of the finest crystals, on the other hand, have been formed in contact with solid material, as on the side of a crack or cavity in a rock. They are then more or less imperfectly developed on the side attached to the matrix (Fig. 567, p. 426).

Surface-Characters of Crystal Faces.—Crystal faces may be *smooth, rough, or curved.* When smooth they possess an evenness and brilliancy

which can scarcely be imitated by any artificial polish, and reflect perfectly clear images of distant objects. This property is utilised in the measurement of crystals by the reflecting goniometer (p. 112). In a perfect crystal the faces are both plane and smooth.

Among the varieties of rough faces two are distinguished by special names.

Drusy faces are those which are composed of minute projecting crystals, as described on p. 94, as in the tetrahedrite from Herodsfoot mine,

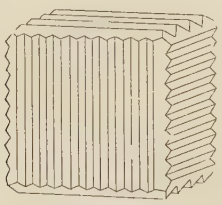


Fig. 442.—Oscillatory Combination.

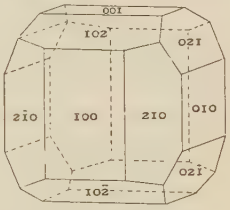


Fig. 443.—Pyrites.

Liskeard, Cornwall, where the drusiness is due to a coating of chalcopyrite, and in crystals of fluor from Redruth (Fig. 446).

Striated faces are marked in one or more directions with fine parallel lines or furrows resembling scratches. These lines are called "striæ"; they may be due (1) to repeated twinning, as in albite (Fig. 254, p. 104);

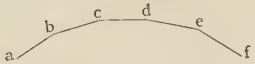


Fig. 444.—Succession of Faces producing a Curved Face.

Fig. 445.—Lenticular Gypsum.

(2) to a repetition of minute crystal faces, as in pyrites (Fig. 86, p. 46). In Fig. 442 the crystal is an "oscillatory" repetition of faces of {210} simulating the combination of Fig. 443.

The *curvature* of faces is generally due not to an oscillatory, but to a progressive succession of vicinal faces (Fig. 444); thus if the angles between the successive vicinal faces *ab*, *bc*, *cd*, *de*, *ef* be sufficiently small, *af* will approximate to a curved surface; when this is so pronounced as to give rise to a lens-shaped crystal, the latter is called *lenticular*. Many crystals of gypsum from Montmartre, near Paris, and from Shotover Hill, near Oxford, are lenticular (Fig. 445).

Aggregation of Crystals.—When two or more crystals are united their union may be either regular—in which case the regularity is due to their crystalline structure—or irregular.

Regular conjunction (which was described in Book I, Chap. II, p. 94) is of three kinds, parallel growth, partially parallel growth, and twinning. The drusiness of crystal faces is generally due to a coating of minute parallel crystals. Fig. 446 represents a drusy crystal of fluor, an octahedron coated with small cubes in parallel position. Re-entrant angles and striations are often produced by twinning.

Fig. 446.—Drusy Crystal of Fluor.

Irregular conjunctions may be—

Radiating, when the crystals diverge from a centre. This is generally characteristic of prismatic and acicular crystals, *e.g.* wavellite (Fig. 447; compare also Fig. 466, p. 332).

Rosette-shaped, when they overlap round a centre like the petals of a rose. This is characteristic of certain tabular crystals, *e.g.* hæmatite from the St. Gothard (Fig. 448).

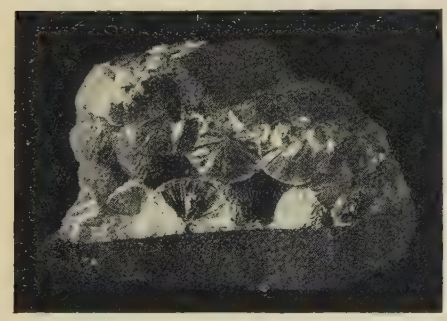


Fig. 447.—Radiating.

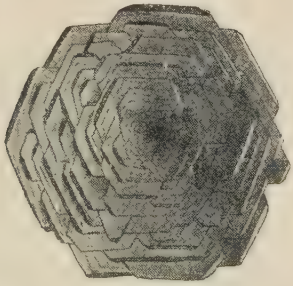


Fig. 448.—Rosette-shaped.

Sheaf-like, when elongated crystals form a bundle or sheaf, diverging at both ends, as in stilbite (Fig. 687, p. 544).

Form and Structure of Crystal Aggregates.—Both the external form assumed by crystalline aggregates, and their internal structure, depend upon the shapes and the mode of aggregation of the constituent crystals. Some of these forms and structures are very characteristic of certain minerals, and they are of importance as indicating in some instances the mode in which the minerals have been formed.

Form.—The following names are used to describe the common forms of such mineral aggregates.

Dendritic, *branched* or *arborescent*, when the constituent crystals diverge from each other and from a common stem, so as to resemble a fern-frond.

This growth is essentially due to a crystalline structure (parallel growth of crystals or twinning), and is illustrated by the manner in which ice crystals form "frost figures" on glass. Among minerals common examples are

Fig. 449.—Dendritic Copper.

afforded by native copper (Fig. 449) and by the frond-like growths of pyrolusite sometimes found in sandstone (Fig. 450), or in the variety of moss-agate known as "Mocha stones."

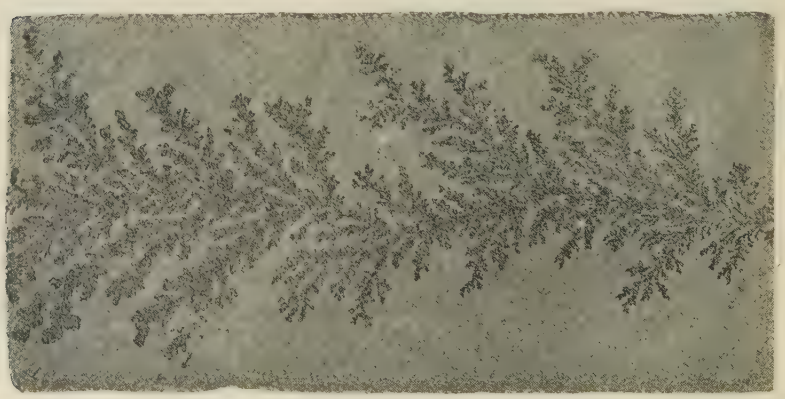


Fig. 450.—Dendritic Pyrolusite.

Mossy.—A similar form in which the sprays and leaflets are more minute. This is also essentially crystalline. Mossy inclusions of chlorite, or of manganese or iron oxides, give its name to "moss-agate" (Fig. 451).

Leafy.—Some minerals, especially the native metals, occur in thin plates or leaves, *e.g.* gold.

Filiform (or *wiry*).—Silver is occasionally found as fine wires.

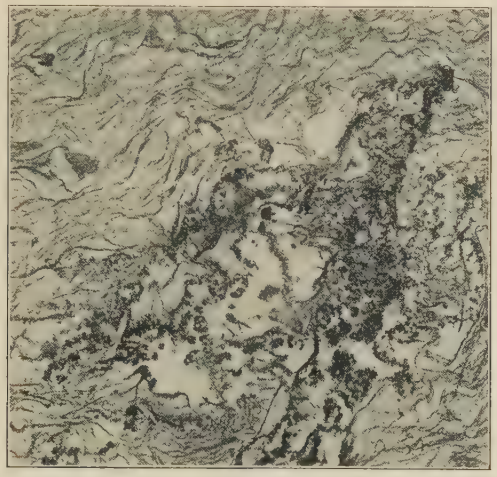


Fig. 451.—Moss-agate.

Globular.—Many minerals occur in spherical concretions, which are generally due either to the deposition of successive coats round a central

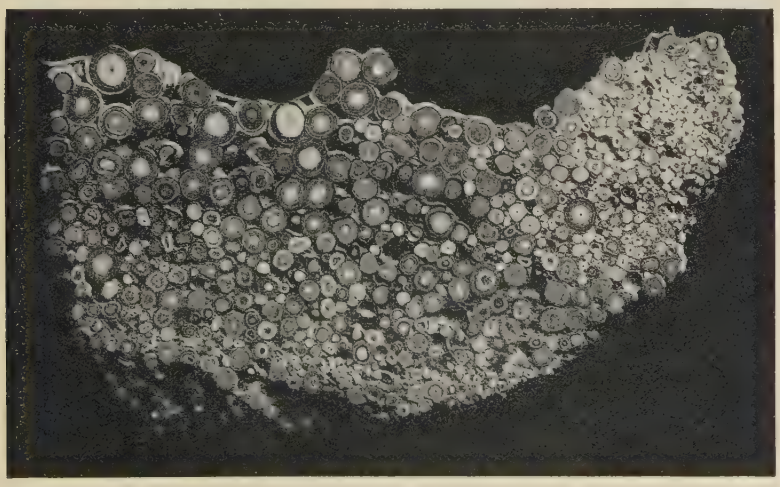


Fig. 452.—Pisolite (section).

granule, like the coats of an onion, as in the pisolites of calcite or aragonite (Fig. 452), or to a radial structure in which the constituent crystals radiate from a centre, as in wavellite (Fig. 447).

Nodular, when the mineral occurs in irregular lumps or nuggets.

Warty, resembling growths of warts.

Mamillary, resembling the nipples of the breast.

Reniform or kidney-shaped. The opal, "menilite," of Menilmontant, near Paris, is a typical example.

Fig. 453.—Coralloidal Aragonite; "Flos-ferri."

Coralloidal, resembling coral in form, *e.g.* the aragonite or "flos-ferri" of Eisenerz in Styria (Fig. 453).

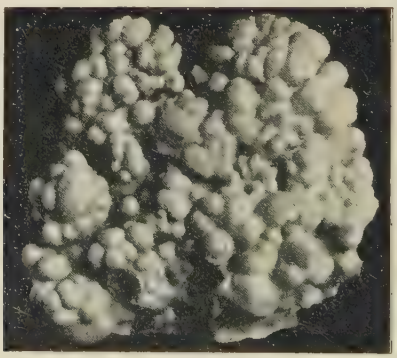


Fig. 454.—Botryoidal Dolomite.

Botryoidal, resembling a bunch of grapes. Fig. 454 represents a botryoidal group of dolomite; but the name is often made to include all such rounded forms as those of Fig. 455, which represents a specimen of hæmatite from Cumberland.

Stalactitic, resembling stalactites, or icicles. Such forms are often produced by dripping solutions; they are generally tapering or cylindrical and composed of crystals radiating horizontally from the central line or axis (Fig. 456).

Fig. 455.—Botryoidal Hæmatite.

Fig. 456.—Stalactite.

Amygdaloidal, or almond-shaped.—The kernels filling steam vesicles or pores in volcanic rocks are known as *amygdales*; they are often hollow and lined with crystals.

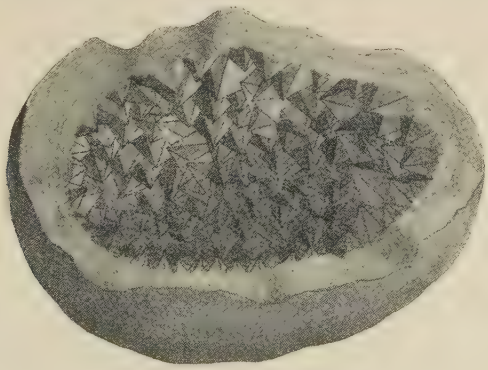


Fig. 457.—Quartz Geode.

Geodes.—Crystals lining a cavity constitute a "geode." Such cavities are also called "druses." The "potato-stones" from Bristol are hollow brown nodules of quartz lined with crystals of the same mineral (Fig. 457); the cavities in flints are often lined in the same way.

Structure.—To describe the varieties of internal structure which accompany the above forms of crystalline aggregates the following terms are used—

Laminar (or *lamellar*), when the constituent crystals or aggregates are tabular and parallel to each other. The terms *micaceous* and *foliated* are also used.

Columnar, when the constituent crystals or aggregates are prismatic and parallel to each other.

Fibrous, when the constituent crystals or aggregates are acicular or capillary.

Granular, when composed of grains or small irregular-shaped crystals.

Massive, when the outlines of the constituent crystals cannot be distinguished by the eye.

Compact, when the constituent crystals are completely invisible to the eye.

Curvilaminar, when composed of curved layers.

Powdery, when composed of minute crystals or grains which are not coherent.

Amorphous Minerals.—Amorphous minerals are of two kinds, *vitreous* (or glassy) and *earthy*.

When vitreous they are uniform masses devoid of any crystalline form or structure (*e.g.* opal). When earthy they are composed of coherent or loosely coherent particles, which are not crystalline (*e.g.* limonite). Many earthy minerals are, however, really aggregates of minute crystalline particles (*e.g.* kaolinite).

Truly amorphous minerals are probably colloidal "gels"; and to this they owe their frequently very variable composition, since a substance in the colloidal state can "adsorb" varying amounts of water and other substances.

Amorphous minerals may assume the various forms described above as globular, nodular, warty, mamillary, reniform, coralloidal, botryoidal, stalactitic, or amygdaloidal. Since, however, they are devoid of crystalline form, the definition of a species which is only known to occur in the amorphous condition can never be regarded as complete. An example of a truly amorphous mineral is opal (colloid silica), which has never been found in crystals.

The amorphous material known as obsidian or volcanic glass is not to be considered as a mineral but as a glassy mixture of silicates, of indefinite composition.

2. **Characters depending upon Cohesion:—Elasticity, etc.**—A mineral in which the constituent particles are coherent opposes a resistance to any force which tends to deform it and alter the relative positions of the particles. If the cohesion is sufficient to prevent any permanent deformation, the particles return to their original position when the force is withdrawn, and the mineral is said to be *elastic*. Such a substance may be to a certain extent bent without breaking, and will return to its

original shape. The word is commonly applied to substances which at the same time have a high *limit* of elasticity, *i.e.* which can be deformed to a considerable extent without being broken or permanently affected. A typical example of an elastic mineral (in this sense) is mica, of which the thin sheets and leaves obtained by cleavage are extremely "elastic."

When the cohesion is not sufficient to restore the original form, the substance remains bent, and is said to be *pliable*. Talc, which in thin leaves might sometimes be confused with mica, is an instance of a pliable as opposed to an elastic mineral. The pliability of *mineral aggregates* is sometimes due to the interlocking of their particles. The flexible sandstone of Delhi consists entirely of angular quartz grains, which dovetail into each other, so that there is a slight play between the particles. In consequence of this structure plates and slabs of the Delhi sandstone may be bent in an extraordinary manner without breaking.

When the particles of a mineral are capable of moving over each other to a considerable extent without losing their cohesion, the mineral is said to be—

Sectile, when it can be cut with a knife without breaking.
Malleable, when it can be flattened by pressure or by a blow with a hammer.
Ductile, when it can be drawn into wires.

Some of the native metals are malleable and ductile; they are, of course, also sectile; every ductile substance is also malleable.

The only common sectile minerals are the following—

Elements—Graphite, bismuth, copper, silver, gold, platinum.
Sulphides—Argentite, molybdenite, realgar, orpiment, tetradymite.
Oxides—Senarmontite, arsenolite.
Haloids—Cerargyrite.

When the particles are free to move over each other to any extent, the mineral is *liquid*, like water or mercury.

Tenacity, Fracture.—When a sufficiently great force is applied the cohesion is overcome, the particles are finally torn asunder, and the mineral is fractured.

The tenacity of any material is measured by determining the breaking strain, or the weight required to fracture a bar of given dimensions. In mineralogy it is only of importance as a determinative quality which is estimated, not measured.

Thus the degree of tenacity is indicated by the following terms, which explain themselves—

Tough, brittle, friable.

The fracture, or nature of the broken surface, is distinguished as—

Conchoidal, when it is curved like a shell; *e.g.* in quartz.

Sub-conchoidal, when it is slightly conchoidal; *e.g.* in crystallised hæmatite.

Uneven; *e.g.* in tourmaline.

Even; *e.g.* in chalcedony.

Splintery, when it is like that of wood. This is especially characteristic of minerals with a fibrous structure; *e.g.* jade.

Hackly, when it is jagged and rough. This is especially characteristic of some metals, and is due to their granular-crystalline structure; *e.g.* copper.

Both crystals and crystalline aggregates may display these varieties of fracture, but crystals also possess the property of plane cleavage, which has already been described (p. 13). The fracture is difficult to obtain in crystals like calcite, which possess a very facile cleavage, since the crystals

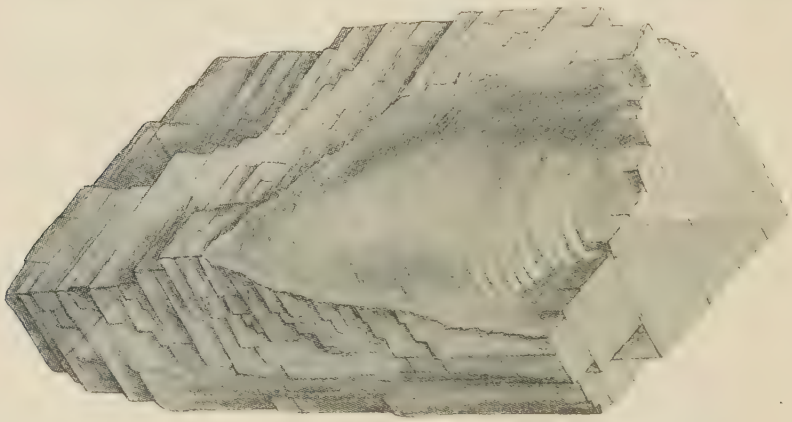


Fig. 458.—Calcite showing Conchoidal Fracture and Cleavage.

generally cleave and will not break in any other way. Fig. 458 represents the rare conchoidal fracture of calcite.

Parting and Cleavage. The *crystals* of some minerals separate along parallel plane surfaces which are not true cleavage-planes, for the crystal cannot be split at any point so as to yield very thin plates, but only at certain places. This *parting*, as it is called, probably takes place along glide-planes or planes of secondary twinning (*cf.* p. 107). Magnetite, for example, possesses an octahedral parting, but no cleavage.

Hardness.—When pieces of two substances are rubbed together, one is generally found to scratch the other without being itself scratched. It is then said to be the harder of the two. The hardness is best tested by drawing a corner of one substance along a smooth surface of the other. The scratch which is made is a line along which the particles have been thrust asunder until their cohesion has been overcome. Thus the hardness depends upon the degree of cohesion. This character is one of considerable value in the determination of minerals.

For this purpose a comparative "scale of hardness" was devised by Mohs for the use of mineralogists, as follows:

Mohs' Scale of Hardness

1. Talc.	6. Orthoclase.
2. Gypsum or rock-salt.	7. Quartz.
3. Calcite.	8. Topaz.
4. Fluor.	9. Corundum.
5. Apatite.	10. Diamond.

The hardness of a mineral is estimated by its capability of scratching, or being scratched by, any mineral in the above list.

A mineral which can scratch fluor, but can be scratched by apatite, is said to have a hardness between 4 and 5, expressed thus: $H = 4\frac{1}{2}$.

The hardness as estimated in this way is no more than a rough approximation, and is by no means a quantity which can be accurately measured; yet in experienced hands it becomes a very valuable aid in the determination of mineral species, since many minerals which resemble each other closely in appearance differ widely in their hardness. For instance, copper pyrites ($H = 3\frac{1}{2}$ to 4) may be readily distinguished from iron pyrites ($H = 6$ to $6\frac{1}{2}$), since the latter is only with difficulty scratched by the knife, while the former yields readily. Again, beryl and apatite are not easily distinguished by their appearance, but beryl has a hardness of nearly 8, whereas that of apatite is only 5.

Where other means of determination are wanting, and even when no minerals belonging to the above scale are available for comparison, the degree of ease with which a mineral may be scratched by the knife is often of the greatest possible use.

Minerals whose hardness is not greater than 2 are scratched by the finger-nail; those of greater hardness than 6 are not scratched by the knife. In many classes of minerals the compounds of silver, copper, mercury, and lead are relatively soft, those of iron, nickel, and cobalt are relatively hard. Minerals, such as corundum and diamond, which, although not compounds of the heavy metals, possess a high specific gravity, possess also great hardness. The hardness of a mineral aggregate is generally less than that of the crystallised mineral itself.

The determinative value of hardness is somewhat diminished by the fact that, like all characters which relate to a direction, it is different upon different faces of the same crystal (being especially low upon planes of cleavage) and even in different directions upon the same face (see p. 123); these variations are, however, slight, and are, generally speaking, far below the intervals between successive numbers on the scale of hardness. In cyanite, however, the hardness is 7 on the face (010) and only $4\frac{1}{2}$ in one direction on the face (100).

3. **Optical Characters.**—When light falls upon a mineral it is partly reflected from the surface and partly refracted into the mineral. A part of the refracted light is reflected or scattered inside the mineral, and emerges again to mingle with that reflected at the surface; a part is

absorbed ; and in transparent minerals a part is transmitted through the substance and emerges on the other side.

The superficial optical characters (lustre and surface-colour) of minerals depend upon the intensity and colour of the light reflected from their surface ; certain other characters (transparency and colour in general) depend upon the light which has been transmitted or has penetrated to a certain depth before emerging.

Lustre.—The intensity of the light reflected from the surface of a mineral is known as its *lustre*, which is described as either *splendent*, *shining*, *glimmering* or *dull*, according to its degree of brightness. It depends to a large extent upon the nature of the surface, being brightest in the case of very smooth surfaces, such as a plane crystal face or a smooth fracture or cleavage-surface. It also depends upon the opacity or transparency of the mineral and (in the case of transparent minerals) upon the refractive index, being greatest where the refractive index is high.

The lustre is distinguished in its quality as—

Metallic—like the surface of polished metal ; peculiar to certain opaque minerals, *e.g.* galena.

Submetallic—less brilliant than metallic ; *e.g.* in hæmatite, magnetite.

Adamantine—nearly approaching metallic, but characteristic of minerals which are transparent, or partly so, *e.g.* blende, cerussite.

Resinous—like the surface of broken resin ; *e.g.* in sulphur, pyromorphite.

Vitreous—like the surface of broken glass ; *e.g.* in quartz.

Waxy—like the surface of wax ; *e.g.* in chalcedony.

The term lustre also includes certain characteristic surface-appearances due to the structure of the mineral. Such lustre is described as—

Pearly—like mother-of-pearl ; shown by minerals having a laminated structure (often due to cleavage) parallel or nearly parallel to the surface, *e.g.* talc.

Silky—generally characteristic of a fibrous structure when the fibres are approximately parallel to the surface ; *e.g.* in gypsum.

Velvety—shown by fibrous minerals whose fibres are approximately perpendicular to the surface, *e.g.* millerite.

Intermediate varieties are sometimes distinguished as metallic-adamantine, metallic-pearly, etc.

True metallic lustre is nearly confined to metals and their compounds with sulphur, arsenic, antimony, and bismuth ; both this and adamantine lustre are characteristic of minerals with a very high refractive index, greater than 2. Thus the refractive index of diamond is 2·42 ; of blende, 2·37 ; of cuprite, 2·85 ; and these minerals all have an adamantine lustre. Many compounds of lead exhibit an inclination to resinous lustre.

Surface-colour.—Many metallic minerals show, when light is reflected from their surface, a characteristic colour which may be quite different from the colour shown by the same material by transmitted light. Thus

stibnite ordinarily shows a grey colour with brilliant metallic lustre, while the light transmitted by very thin cleavage-flakes is deep red. Hæmatite in crystals is black with submetallic lustre, but blood-red in thin flakes. Similarly very thin gold leaf is green by transmitted light.

Diaphaneity.—If objects can be clearly seen through a mineral it is said to be *transparent*; if light penetrates, but not sufficiently to enable objects to be seen, the mineral is said to be *translucent*; intermediate degrees of transparency are distinguished as semi-transparent and semi-translucent; other minerals are said to be *opaque*, but many of these are feebly translucent in very thin sections, *e.g.* hæmatite.

Refractive Power.—Many of the superficial characters of minerals, whether crystals or aggregates, depend upon their refractive index. Such are their lustre (as described above) and their visibility when immersed in a liquid. Methods by which the latter may be used to estimate the value of the refractive index will be found in the next chapter (p. 323). Accurate methods of determining refractive indices have already been described in Book I, Chapter VII.

Dispersion.—The light which enters a transparent mineral is differently refracted according to its colour, blue rays being refracted more than yellow, and yellow rays more than red. Hence a beam of white light becomes separated into its component colours.

This character gives rise to the "fire" displayed by certain precious stones. A stone having strong dispersive power splits the incident white light into coloured beams which may diverge widely, whereas a stone of weak dispersive power throws out practically only white light.

The dispersion is usually measured by the difference between the refractive indices for violet and red rays, for example—

	Violet	Red	Dispersion
Diamond	$\mu = 2{\cdot}465$	2·402	0·063
Rock-crystal	1·564	1·539	0·025
Fluor-spar	1·437	1·431	0·006

The high dispersive power of diamond adds much to its value as a precious stone; the low dispersion of rock-crystal permits this mineral to be used for spectacles, etc.; and the very low dispersion of fluor has led to its employment in "apochromatic" microscope lenses.

Colour.—Apart from the peculiar surface-colour shown by some metallic minerals, as mentioned above, the colour of minerals is of two sorts, since it may be due (1) to physical causes, *i.e.* to interference, like the colour of mother-of-pearl; (2) to chemical causes, *i.e.* either to the chemical composition of the pure mineral itself or to colouring matter which it contains.

In the first case the colour will vary with the direction in which the surface is viewed.

Colour due to Physical Causes.—As explained on p. 135, when two smooth plates of glass are pressed together bright bands of colour appear between them, due to the interference of light reflected by the intervening

film of air. Similar colours are often seen on cracks and flaws in glass or in transparent minerals.

This interference of reflected light plays an important part in some of the optical properties of minerals which have a finely laminar structure, or those which enclose very thin plates or rods of other minerals.

The following terms are used in describing such effects :

Play of Colours signifies the irregular and shifting flashes of colour, such as impart its peculiar beauty to the precious opal.

Change of Colours signifies the property of exhibiting different colours by reflected light when viewed in different directions, such as belongs to smooth surfaces of labradorite ; in this mineral it is due to fine lamellar inclusions or fissures (p. 527).

Iridescence denotes the broad bands of colour due to the presence within the mineral of thin films (often of air in cracks) of varying thickness, which give rise to a series of different tints.

Opalescence is a peculiar milky appearance observed in the interior of some minerals, notably the translucent varieties of opal.

In " cat's-eye " it takes the form of a single band of opalescent light traversing the mineral in one direction (" chatoyance "), and has the appearance of being due to a fibrous structure.

Tarnish is a superficial iridescence produced by the formation upon the surface of the mineral of a fine film of some decomposition product (often an oxide) which gives rise to the colours of thin plates.

Among minerals chalcopyrite is the most conspicuous instance, and the beautifully tarnished specimens of this mineral are commonly known by the name of " peacock-copper."

Colour due to Chemical Causes. The colour-names generally used by mineralogists are those which were drawn up by Werner in the latter half of the eighteenth century. In this scale of colours a distinction is made between the colours of opaque minerals with metallic lustre and those of other minerals. The scale of colours with their various *shades* is as follows :

Metallic Colours

Red—copper-red.
Yellow—bronze-, brass-, gold-yellow.
Brown—pinchbeck-brown.
White—silver-, tin-white.
Grey—lead-, steel-grey.
Black—iron-black.

Non-metallic Colours

White—snow-, reddish-, yellowish-, greyish-, greenish-, bluish-, milk-white.
Grey—bluish-, pearl-, reddish-, smoke-, greenish-, yellowish-, ash-grey.
Black—greyish-, velvet-, greenish-, brownish-, reddish-, bluish-black.
Blue—blackish-, azure-, violet-, lavender-, plum-, prussian-, smalt-, indigo-, duck-, sky-blue.
Green—verdigris-, celandine-, mountain-, leek-, emerald-, apple-, grass-, pistachio-, asparagus-, blackish-, olive-, oil-, siskin-green.

Yellow—sulphur-, straw-, wax-, honey-, lemon-, ochre-, wine-, cream-, bay-, pea-, orange-yellow.
Red—aurora-, hyacinth-, brick-, scarlet-, blood-, flesh-, carmine-, cochineal-, rose-, crimson-, peach-blossom-, columbine-, cherry-, brownish-red.
Brown—reddish-, clove-, hair-, chestnut-, yellowish-, wood-, liver-, blackish-brown.

Colour, except in the case of a few minerals, is a character of very little value in the discrimination of species, since most minerals derive their colour from a trace of some impurity which is not essential to the mineral, or from isomorphous intermixture of various compounds.

Fluor-spar, for instance, which in its purest state is quite colourless, is more often found tinted with various shades of either green, blue, or yellow, and sometimes red, and one and the same mineral specimen, even the same crystal, may be banded with layers of different colours. Moreover, a mineral in very thin slices, when it is viewed mainly by transmitted light, may present a colour very different from that which it has in the mass when viewed mainly by reflected light; black blende, for example, appears brown or even yellow in thin fragments; and the colour of thin fragments of the same mineral may vary largely, owing to the different amounts of absorption by different thicknesses of the substance. The above scale is more useful to describe differences of colour than to define any constant character of minerals; but since the estimation of colour varies with different persons, the scale is of little practical use, except when referred to a standard series of minerals such as those exhibited in many large mineral collections.

An attempt to define colour by means of a standard series of pigments has been made in Radde's *Internationale Farben-skala*, which is sometimes referred to by mineralogists.

Streak.—A mode by which colour is made of real value in the discrimination of species consists in observing the colour, not of the mineral as it ordinarily occurs, but of its powder, so that any variations due to structure or thickness are eliminated. The colour of the powder, or the *streak* of the mineral, is a feature of some constancy. A distinction was formerly made between the "streak" (the term being then employed to denote the colour of the scratch made upon a mineral by an edge of some harder substance) and the "colour of the powder," as seen upon a white surface; in this sense, however, the streak was merely the colour of the powder as seen upon the mineral itself. The only systematic method of observing the streak consists in scratching off a little powder or a small fragment from the mineral and crushing it with the blade of a knife upon a sheet of white paper, or the mineral may be rubbed upon a piece of unglazed porcelain. The streak so obtained is sometimes very different from the colour of the mineral, and is a more constant character than the latter.

The streak is especially valuable in distinguishing between the opaque metallic minerals, for which other optical methods are not available, and which are too heavy to be tested by heavy liquids. Thus iron pyrites

and copper pyrites are somewhat similar in appearance, but the streak of the former is somewhat lighter than that of the latter, and this character, combined with the hardness, is quite sufficient to distinguish the two species.

Phosphorescence.—Some minerals become luminous at a temperature far below that of red heat, either by friction, by heating, or by exposure to light, to the electric discharge, or to X-rays; such minerals are said to *phosphoresce*. Diamond and some varieties of fluor, if exposed to sunlight and then taken into a dark room, appear strongly luminous; quartz becomes luminous by friction with quartz; mica emits flashes of light when cleaved; the same feature is observed in potassium chloride during crystallisation; and some varieties of fluor phosphoresce when raised to a temperature less than that of boiling water.

This property was known in the diamond in very early times, and at the beginning of the seventeenth century it was discovered by Cascariolo of Bologna that barytes, by ignition with charcoal, becomes capable of phosphorescence after exposure to light (owing to the formation, as is now known, of barium sulphide).

Phosphorescence is most beautifully shown when the substance is enclosed in a vacuum tube and exposed to the electric discharge of a Ruhmkorff coil; diamond, blende, and other phosphorescent minerals are by this process made to glow with a brilliant light.

The colour of the light emitted by a phosphorescent mineral which has been, for example, exposed to sunlight, varies with the nature of the mineral and also with the temperature at which the observation is made. The effect is always temporary; after a few hours (as in the case of calcium sulphide), minutes, or seconds (as in the case of aragonite), the substance ceases to glow, until it has been again subjected to the influence which excites the phosphorescence.

The property of phosphorescence consists, then, in the power possessed by certain substances of transforming energy communicated to them by one of the above methods into visible radiations, and continuing to do so, after the exciting agent has ceased to operate.

It is always found that when this energy has been communicated in the form of light rays, the rays emitted have a greater wave-length than those received.

Fluorescence.—Allied to phosphorescence is the property known as *fluorescence*.

Some crystals of fluor, when examined in sunlight, possess a peculiar milky or hazy appearance which only extends to a slight depth below the surface, and diffuse a bluish or greenish light from this superficial layer. It is the ultra-violet or non-luminous rays of the solar spectrum which are especially capable of exciting fluorescence in such crystals.

Here, again, the rays which are received by the mineral are transformed within its substance, and are emitted as diffused light of greater wave-length; but the effect lasts only so long as the mineral is illuminated.

A similar effect is produced by X-rays and by the rays emitted by radioactive substances; and a screen covered with powdered wurtzite is in common use as a means of detecting these rays.

The colour of the light diffused from the surface of a fluorescent mineral is quite distinct from that of the mineral as seen by transmitted light. Thus some of the purple fluor of the North of England, if viewed by transmitted light, appears green.

Little is known of the cause of this effect. In the fluorescent amber of Sicily it is said to be connected with the presence of a vast number of microscopical cavities.

4. **Other Characters :—Magnetism.**—Comparatively very few minerals possess the property of magnetism to any marked extent. Magnetite, which was formerly known under the name of the lodestone, and in which the magnetic character was originally discovered, is the only mineral which exhibits " polar " magnetism in any degree. Pieces of magnetite frequently possess a north and south pole, one of which repels, and the other attracts, the north pole of a magnetic needle, and either of which will attract iron filings ; this property is also exhibited, though in a far less degree, by a few other minerals, such as pyrrhotite and platinum. Ordinary magnetism, which is the power of being attracted, like iron, by either pole of a strong magnet, or of attracting either pole of a magnetic needle, is a property of several minerals containing iron. Such minerals are described as *magnetic*.

Advantage is taken of this property in order to separate magnetic from non-magnetic minerals by means of an electromagnet (see p. 218).

Many ferriferous minerals which are not magnetic can be made so by fusion, owing to the formation of magnetic oxide of iron, so that the property is also of importance in the examination of minerals by the blowpipe.

Electricity.—Like other substances, minerals become electrified by friction ; among those which are non-conductors of electricity, and upon which consequently this property may be observed without insulating the mineral, may be mentioned quartz, which becomes positively electrified, and sulphur, which becomes negatively electrified, by friction with such substances as cloth or wool.

The minerals which are good conductors of electricity are the metals, and many of the minerals possessing metallic lustre.

For a method of separating conducting from non-conducting minerals see p. 218.

When two different minerals, both conductors of electricity, are placed in contact and made to form part of a conducting circuit, and are heated or cooled at their surface of contact, a thermo-electric current passes from the one to the other ; this property is very marked when the two substances chosen are antimony and bismuth.

The separation of electric charges on certain crystals which have polar symmetry during change of temperature (pyroelectricity) has been already described (see p. 129).

CHAPTER II

THE DETERMINATION OF MINERALS

In order to determine the nature of a mineral with certainty and to fix its place in the system, if it be a new compound, nothing is satisfactory save a complete quantitative analysis, combined with a measurement of the crystal angles and of the physical constants.

In general, however, the specimen under examination belongs to a known species whose properties have been more or less completely determined, and it is only necessary to ascertain to which of the known species it is to be referred.

For this purpose it is in general sufficient to prove that it corresponds with some well-determined mineral both in its chemical reactions and in its crystalline form. To determine the crystalline form with certainty some of the physical properties must also be examined, especially, if possible, the optical characters in parallel and convergent light; even if the crystals cannot be measured the optical characters in themselves are often decisive. The most valuable confirmatory evidence is supplied by the specific gravity.

In order to use as little of the material as possible it is highly advisable to apply physical tests first, since they involve scarcely any destruction of the mineral.

For the same reason, when chemical tests are subsequently applied, the first should be such as can be effected by the blowpipe and by reactions on a minute scale viewed under the microscope.

Further, it is extremely important that the chemical characters should be determined upon the *very material* which has been used for the physical examination; if this be not done there is no certainty that the two sets of properties really belong to the same substance.

1. **Physical Examination.**—Except after long experience among minerals the external aspect of a specimen is of little value as an aid to its determination. Only in one respect is the appearance of a mineral of real use; if it possesses metallic lustre it is probably either a metal or belongs to the class of metallic minerals, *i.e.* the sulphides (including arsenides, antimonides, selenides, and tellurides) or the sulpharsenites (including sulphantimonites and sulphobismuthites). This is a useful guide and a great help in determinative mineralogy. The great class of silicates have, for the most part, a vitreous lustre; so also have many of the carbonates and sulphates.

The metallic minerals are usually nearly opaque, hence optical examination is with them generally impossible ; but the streak and hardness should be noted, and chemical tests (especially those with the blowpipe on charcoal) should then be at once applied to them.

But if a mineral be transparent it should before all things be examined in the polarising microscope in the following manner : A small fragment, having been placed in a drop of oil or water on a glass slide, is broken with the blade of a knife ; this gives at once some idea of (1) the hardness of the mineral, and (2) its cleavage ; the drop of liquid prevents any of the fragments flying away during fracture. Viewed under the microscope the clearness of outline and visibility of the surface will indicate whether the fragments have a refractive power near that of the liquid or widely different from it (see p. 325).

The polariser is then inserted and the presence or absence of dichroism is noted.

The analyser being next inserted, and care being taken that the nicols are crossed, it can at once be seen whether the mineral is isotropic or not. If it possesses birefringence, the extinction-angles of the cleavage-flakes or of crystalline faces (if they are sufficiently large or characteristic to be identified) should be measured. For this purpose the crystals or cleavage-fragments should be turned over in the drop and viewed in different directions. Compensation with the quartz wedge will give some measure of the birefringence, and, if the crystals be needles, will show (as described on p. 196) whether they are elongated in a positive or negative direction ; *i.e.* whether the axis of the needle is the vibration-direction corresponding to the greater index of refraction or to the less.

Finally, the fragments, being immersed in a drop of oil, are to be examined in convergent light, if necessary with an immersion objective, and the interference-phenomena observed. It will in general be necessary to hunt among the fragments for one which shows the optic axis or axes, and to turn it about with the point of a needle into an appropriate position. For this purpose viscid cedar oil will be found a very convenient medium.

An alternative method, which is used particularly for the determination of the mineral constituents of rocks and has been developed in great detail for this purpose, consists in examining under the microscope a slice of the rock which has been ground down thin enough to be transparent and mounted in Canada balsam. The form of the crystals of any of the constituent minerals (supposing these to have had room to develop faces) and their cleavage (if any) can be inferred from the outlines of their sections and the arrangement of cleavage-cracks. Their refractive power may be estimated from the appearance of the surface (see below), and their double-refraction and other optical characters can be determined as with fragments, but with the additional convenience that the various sections in the slice are all of equal thickness, though cut in different directions.

The explanation of the method of estimating the refractive index of a mineral from the appearance of its surface in a section is as follows. The surface of a piece of ground glass seen in air appears rough, since the light is irregularly refracted or reflected at its rough surface, but if placed

in a liquid whose refractive index is the same as its own, it appears smooth and transparent since the light is no longer refracted and scattered at its surface. Similarly the surface of a mineral grain in a rock section, which is more or less rough from the grinding, will be visibly rough, or apparently smooth, according as its refractive index differs much or little from that of Canada balsam (1·536). Thus in a rock section a crystal of olivine ($\beta = 1{\cdot}678$) appears quite rough, with all the unevenness due to the grinding, whereas a crystal of orthoclase felspar ($\beta = 1{\cdot}523$) appears almost smooth. A mineral like olivine, whose refractive index differs considerably from that of the balsam, is said to show "high relief," while orthoclase shows "low relief." It should be observed that a mineral whose index is considerably *lower* than that of balsam will also show high relief, *e.g.* fluor ($\mu = 1{\cdot}43$); but such minerals are somewhat rare in rocks.

The following method, due to F. Becke, may be used to determine which of two minerals in contact with one another in a rock section has the higher index. Let the junction between the two minerals be viewed with a low power under the microscope, the condenser being removed. The line of contact will be clearly visible if the two minerals differ in their refractive power. If the objective be slightly raised, a bright band of light will be seen along the boundary just *within* the more refractive mineral. If the objective be slightly lowered, the bright band passes across the junction to the side of the less-refractive mineral. The same appearance will of course be seen where a mineral is in contact with balsam at the edge of the section. This effect enables the observer to detect very slight differences of refractive index if the contact be sufficiently well defined. The appearance of the section is somewhat as shown in Fig. 459, which, however, corresponds to oblique illumination produced by swinging the mirror to one side. The index of balsam lies between those of albite and anorthite, so that it is possible by this method to ascertain approximately the refractive index and therefore the nature of a plagioclase (*i.e.* a soda-lime-) felspar in a rock section.

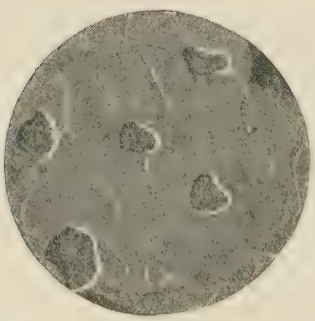


Fig. 459.

The bright band is caused by deflection of the light rays at the junction between the two minerals, either by refraction or total reflection according to the inclination of the junction to the plane of the section. The light is deflected *towards* the mineral which has the higher index, as shown in Figs. 460, 461, which represent parallel rays traversing the section perpendicularly except where they strike the junction. The deflected rays cross the directly transmitted rays obliquely, and if the objective be raised until its focus lies on the dotted line *ab*, both sets of rays will appear to be diverging from a point on the side of the more refractive mineral (as *c*); this point will therefore appear brighter than the surrounding parts, and the junction will appear to be edged by a bright

border on this side. If the objective be lowered till its focus lies on the dotted line *cd* the illuminated border will move to the other side of the junction (as at *f*). (*cf.* G. W. Grabham, *Min. Mag.* 1910, vol. xv, p. 342).

In the course of the microscopic examination much will have been learnt regarding the mineral, whether it is isotropic, uniaxial, or biaxial, or pseudo-symmetric, whether it is simple or twinned; an estimate will have been formed of its refraction and birefringence, of the sign of the latter, and of the axial dispersion. The optic axial angle may even be approximately measured by noting the number of divisions which the interval between the axes occupies on an eye-piece micrometer which has been previously calibrated by means of known sections.

It is most important also to note, with a view to the subsequent chemical examination, whether the mineral is pure or contains inclusions.

A fragment can then, if the mineral be not too heavy, be dropped into a heavy liquid and the specific gravity determined as explained on p. 213.

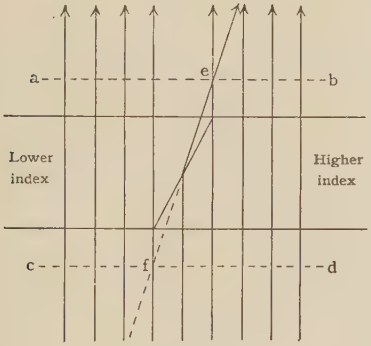


Fig. 460.

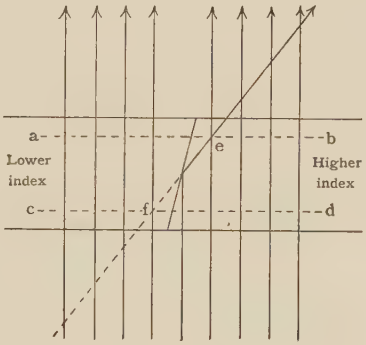


Fig. 461.

If the material is very heavy it may be expected to contain lead or one of the other heavy metals, or barium; the transparent lead compounds often possess also a rather adamantine or resinous lustre.

If crystals with plane faces are available they should be measured with the goniometer, special care being taken to identify the faces through which optic axes are visible and those whose extinction-angles have been ascertained.

Measurements should also be made of the refractive index (if it is sufficiently low) by means of the total reflectometer, provided that a sufficiently large plane crystal-face or cleavage-surface can be found; or the refractive index may be determined under the microscope by the following method, which has been developed by Schroeder van der Kolk.

If a fragment of a transparent mineral be placed in a drop of liquid and examined with a low power under the microscope it usually appears transparent in the centre only, and dark near the edge. The distinctness of the dark border depends upon the refractive index of the liquid used, and if this is the same as that of the mineral the border vanishes and the whole fragment appears transparent. The cause of this will be clear

from the diagrams (Figs. 462 and 463), in which M represents the fragment of mineral surrounded by liquid, and O the microscope objective. In Fig. 462 the refractive index (μ_m) of the mineral is higher than that (μ_l) of the liquid, while in Fig. 463 the indices are reversed (as suggested by the shading). A fragment is usually more or less lenticular in form, being thinner at the edges than in the centre, and if its refractive index is greater than that of the surrounding liquid, parallel rays will be refracted as shown in Fig. 462, those traversing the edge of the fragment being deviated so much as to pass outside the microscope objective. If the refractive index of the mineral is less than that of the liquid, the refraction is as shown in Fig. 463, rays from the edges again passing outside the objective.

In order to determine whether the index of the mineral is higher or

Fig. 462.—$\mu_m > \mu_l$.

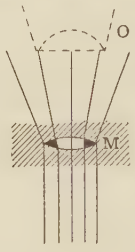


Fig. 463.—$\mu_m < \mu_l$.

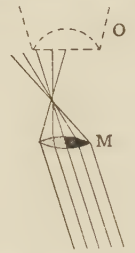


Fig. 464.—$\mu_m > \mu_l$.

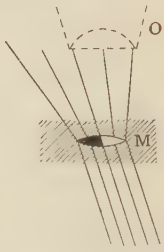


Fig. 465.—$\mu_m < \mu_l$.

lower than that of the liquid, the mirror is swung to one side, so as to give oblique illumination. The path of the rays is then as shown in Figs. 464 and 465, one side of the mineral grain appearing bright while the other is dark. If the mineral has the higher index (Fig. 464) the part of the grain on the side from which the light comes will be dark, while the other side is bright, and *vice versa*. It must be noted that this appearance will be reversed in the image as seen in the microscope.

A series of liquids is prepared, of known refractive indices, and grains of the mineral are examined in them in succession, with oblique illumination, until the absence of a dark shadow shows that the indices of grain and liquid are equal.

The following series of liquids is recommended:

	Refractive Index at 15° C.		Refractive Index at 15° C.
Carbon tetrachloride	1·462	Anilin oil	1·583
Beech nut oil	1·475	Bromoform	1·590
Xylene	1·487	Cinnamon oil	1·605
Cedarwood oil	1·505	Mono-iodobenzene	1·619
Monochlorbenzene	1·523	α-Monochlornaphthalene	1·635
Ethylene bromide	1·536	α-Monobromnaphthalene	1·655
Clove oil	1·544	Equal volumes of methylene iodide and α-Monobromnaphthalene	1·700
Nitrobenzene	1·552	Methylene iodide	1·740
Monobrombenzene	1·561		

Since the dispersion (*i.e.* the difference of the refractive indices for

different colours) is stronger in the liquids than in most minerals, a grain which has the same index as the liquid for yellow light will be more strongly refractive for red rays and less so for blue. It will therefore appear coloured at the edges, showing red at the side which was bright in Fig. 464, and blue at the bright side of Fig. 465. This colour-effect, when observed, indicates that the refractive indices of the mineral and liquid are very nearly equal.

If a crystal has been measured and its optical properties ascertained, and if measurements have also been made of the specific gravity and refractive index, it will often be found that sufficient *numerical* data have been obtained for the identification of the mineral, by means of the tables on pages 620 to 631; a few simple qualitative chemical tests will then suffice as a confirmation.

In many cases, however, it is necessary to know something about the composition before even a guess can be made as to the species.

2. **Chemical Examination.**—For the practical determination of minerals, when it is only required to refer a specimen to some known species, the methods of quantitative analysis are not necessary; simple qualitative tests, combined with the physical and crystalline characters of the mineral, are generally sufficient to distinguish one species from all the others.

(*a*) *Pyrognostic Examination, or Dry Tests.*—The mineral is heated either in a closed or open tube, or upon charcoal, aluminium, or platinum, for the purpose of fusion, sublimation, oxidation, or reduction; or else it is fused with fluxes in a loop of platinum wire, for the purpose of obtaining the characteristic (coloured) products which are yielded by certain elements.

(*b*) *Solution-reactions, or Wet Tests.*—The mineral is subjected to the action of various solvents, generally water or acids; the resulting solutions are tested with reagents, and the precipitates produced are distinguished by their colours and solubilities according to the ordinary methods of qualitative analysis.

Since the results of qualitative analysis are not expressed numerically, they lack the precision of physical and crystallographic methods; it is therefore very important to check the chemical examination by the use of *comparative tests*. The reactions of the mineral examined should be carefully compared with the same tests applied to the same quantity of an undoubted sample of the mineral species to which it is referred, or of minerals which it resembles.

As the most important of all preliminary chemical tests, a mineral should first be treated with a drop of hydrochloric acid, when effervescence will denote the presence of a carbonate, and the evolution of hydrogen sulphide a sulphur compound.

(*c*) *Spectroscopic Examination.*—The emission or absorption spectra given by some minerals are characteristic.

(*a*) Pyrognostic Reactions

Fusion and Volatilisation.—Most minerals when heated pass more or less readily into the liquid state. Some fuse at a high, and some at a

low temperature, and it is often possible to distinguish between minerals which have nearly the same appearance by observing their relative temperature of fusion. For this purpose a small splinter of the mineral is held in a platinum forceps and the blowpipe flame is directed upon its edge. Some minerals, such as (1) stibnite and (2) natrolite, fuse readily to a globule, the former even in a candle flame; (3) almandine garnet fuses with greater difficulty; (4) actinolite and (5) orthoclase only become rounded on thin edges; (6) bronzite shows only slight traces of fusion even in very thin splinters, while (7) quartz is infusible before the ordinary blowpipe.

Upon these seven species von Kobell founded a scale of fusibility. A mineral, for example, which fuses more readily than actinolite but less readily than almandine is said to have a fusibility between 3 and 4; one which in this respect lies between orthoclase and bronzite is said to have a fusibility between 5 and 6.

This scale is usually given in tables for the determination of minerals; in reality, however, the intervals between its successive members correspond to very unequal differences of temperature. Penfield proposed chalcopyrite in place of natrolite for 2.

The determination of the actual temperature of fusion of a mineral is a matter of some difficulty, requiring special apparatus, and it is generally sufficient for determinative purposes to ascertain merely whether the mineral is fusible with ease or difficulty, or for the purposes of diagnosis to determine whether it is more or less fusible than the minerals with which it might be confounded.

No minerals are, in reality, absolutely infusible when subjected to such temperatures as those of the oxyhydrogen flame or the electric arc; but many—especially silicates—are infusible in the flame of the ordinary mouth blowpipe.

In testing fusibility the oxidising flame should be used. During fusion the properties of the mineral are usually changed. Minerals containing water often intumesce, or spit; those which yield gases may become slaggy or may decrepitate. Minerals containing much iron generally fuse to a magnetic globule, owing to the formation of magnetic oxide of iron.

Colour imparted to Flame.—When held in the non-luminous flame of a Bunsen burner, minerals which contain certain volatile elements impart characteristic colours to the flame. The reaction is often made more apparent by previously moistening the mineral with hydrochloric acid, which may combine with some of the metals to form volatile chlorides. The colours imparted to flame should be observed at the same time with the fusibility. They are given in Table A (p. 617).

The colours may be completely masked when the mineral contains enough sodium to give a very pronounced yellow flame.

During this process the smell given off should be observed and compared with the list in Table D (p. 618).

Sublimation—Heating in Closed Tube.—When the mineral is heated in a glass tube (formerly called a matrass) closed at the lower end (which

may be conveniently in the form of a bulb) any condensible vapours which are given off will be deposited as a sublimate upon the cool sides of the tube. For this purpose a small portion of the mineral is powdered or broken into minute fragments before being introduced into the tube. Any changes of colour which take place as the sublimate cools should be noted. The characteristic sublimates are given in Table B (p. 617).

Phosphates may be recognised by heating the powder in a closed tube with a piece of magnesium ribbon ; the phosphate is reduced to phosphide, which gives the characteristic smell of phosphoretted hydrogen on adding a drop of water.

Oxidation—Heating in Open Tube.—When the powdered mineral is heated in a glass tube open at both ends and held in a slanting position, so that a free current of air can rise through it, oxidation products are yielded, which may either be deposited as sublimates, or may issue as characteristic vapours.

The sublimates are given in Table C (p. 618).

The vapours are given in Table D (p. 618).

Reduction—Heating on Charcoal, etc.—Many metallic oxides and oxysalts may be deprived of their oxygen by fusion upon charcoal either alone or mixed with sodium carbonate, when certain incrustations and fusion products are produced ; the former are generally oxides having characteristic colours ; the latter are often fusible metals.

For this purpose the mineral is to be powdered and intimately mixed with about four times its bulk of sodium carbonate, slightly moistened with water, and heated before the reducing flame of the blowpipe in a cavity scooped out of a charcoal support. The characteristic incrustations are given in Table E (p. 618).

When metallic particles are produced they serve to confirm and distinguish these determinations, and also to reveal the presence of copper, lead, gold, etc. If a very minute quantity of the mineral be employed the metallic bead is best observed by breaking up the fused mass in a little water in an agate mortar and washing off the suspended charcoal ; the sodium carbonate is dissolved and the glittering metallic particles are then easily detected and examined. They may be any of those given in Table F (p. 618). These particles may be dissolved in acid or *aqua regia* and tested by the ordinary methods of qualitative analysis.

Sulphur compounds should first be converted into oxides by a preliminary " roasting " in the tip of the oxidising flame before treatment as above.

During fusion on charcoal any smell should be observed ; the indications will be those of Table D. If there is an infusible residue it should be treated with cobalt nitrate ; see Table K (p. 619).

Fusion with Fluxes :—Borax Bead.—When borax is heated with minerals containing certain metallic elements it decomposes them and combines with the oxides of these metals to form glassy compounds having characteristic colours.

For this purpose the borax is fused before the blowpipe in a small

loop of platinum wire to a transparent bead; a very minute portion of the powdered mineral is then brought into contact with the bead after slightly moistening it with water, and the bead is again fused until the mineral is completely dissolved.

Sulphides, arsenides, etc., must first be converted into the form of oxides by roasting.

The colours imparted to the bead by exposure to the oxidising and reducing flames of the blowpipe are then observed. They may be one or more of those mentioned in Table G (p. 619).

Microcosmic Salt Bead.—The treatment in the bead of microcosmic salt is the same as with borax. The colours are for the most part the same as those of the borax bead. The particulars in which they differ are given in Table H (p. 619).

Treatment with Cobalt Nitrate.—Infusible minerals, after being heated, are to be moistened with solution of cobalt nitrate and ignited in the oxidising flame; this may impart to the mineral one or more of the characteristic colours given in Table K (p. 619).

This treatment is especially valuable as a test for aluminium and zinc; it should always be applied to any infusible residue obtained by heating the mineral on charcoal.

(*b*) Solution-reactions

Solution.—Comparatively few minerals are soluble in water; many, however, are dissolved either wholly or in part by hydrochloric or nitric acid, or by *aqua regia*, while a large number are insoluble in any of these reagents. Most of these latter may be decomposed by fusion with sodium carbonate or "fusion mixture." The acid portion is thereby converted into a sodium salt, which is soluble in water, while the bases are mostly separated as oxides, which, after filtration of the solution, may be dissolved in hydrochloric acid and separately examined.

Many minerals are only attacked with great difficulty and on prolonged heating with the solvent; they should therefore be finely ground in an agate mortar before treatment, to expose a large surface to the reagent. Some are decomposed by solvents with separation of a residue which must be examined separately. A few, such as diamond, are entirely insoluble.

In testing a mineral with acid solvents first the dilute and then the concentrated acid should be employed.

It will be found that among the minerals soluble in water are all the simple compounds of the alkali metals; many sulphates—but not the basic sulphates; all the nitrates; few oxides; no sulphides or sulphosalts; no silicates.

Partially soluble with a residue are many double salts, *e.g.* gaylussite, $CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$, from which the sodium carbonate is dissolved out.

It appears further that among the minerals completely soluble in hydrochloric acid are some of the oxides, some manganites, and all the

carbonates (except cerussite); also many phosphates and arsenates, and some sulphates. The carbonates give off CO_2 with effervescence; the manganites give Cl_2 by oxidation of the acid. Some sulphides give off H_2S, which blackens filter-paper moistened with lead acetate.

Most sulphides are decomposed by nitric acid with separation of sulphur.

Some silicates are decomposed by hydrochloric acid, which dissolves out the bases, leaving a residue of powdery or gelatinous silica, but many minerals of this group require fusion with alkaline carbonate. Such insoluble silicates may also be decomposed by treatment with a mixture of hydrofluoric and sulphuric acids, which converts the silica into gaseous SiF_4, leaving the bases in solution as sulphates.

The Testing of Solutions (either of the minerals themselves or of their soluble products after fusion, etc.)—The majority of minerals are complex compounds containing more than one base and often more than one acid radical. These are to be separated from each other as insoluble precipitates by the usual methods, for which reference must be made to a book on chemical analysis. All the elements present in a complicated mineral may be discovered with greater certainty in the solutions than by pyrognostic methods alone, because they can be more effectively separated. The object of an analysis is to ascertain—firstly, to which of the great classes of minerals the substance belongs, by the determination of its predominant acid radical; and, secondly, what are its basic elements. Each determination is to be checked by one or more of the pyrognostic tests. The chromates, arsenates, silicates, sulphides, arsenides, and sulphosalts will have been already detected by these tests.

Microchemical Reactions.—Some solution-reactions give rise to crystallised precipitates whose form is so characteristic that they may be recognised under the microscope.

For this purpose a drop of the solution is placed on a microscope slide and brought into contact with a drop of the reagent placed close to it. If the solutions are sufficiently dilute the precipitate crystallises slowly and in distinct crystals. The chief advantage of microchemical methods lies in the minute amount of material required; in fact a number of the reactions mentioned above may be effected under the microscope with a mere grain of the mineral; and the processes of solution, evaporation, and precipitation may, with a little practice, be carried on upon the microscope slide instead of in a test-tube or beaker. Even filtration may be successfully effected by a slip of filter-paper, which carries off a drop of solution and leaves the solid residue behind.

But it will be sufficient here to confine our attention to a few of those reactions which yield crystals of typical form easily recognisable by their appearance and optical properties, especially those reactions which indicate elements difficult to determine by the preceding methods, such as Al, Si, Mg, Ca, U, K, Cs, Na.

Calcium.—One of the best and most typical precipitates is that of gypsum, produced (for example) by very dilute sulphuric acid mingling

with a drop of solution of a calcium salt (Fig. 466). Careful examination shows that these crystals possess the characteristic form of the mineral gypsum; some are simple tablets; some are arrow-head twins; and they have an extinction angle of $37\frac{1}{2}°$ viewed through (010).

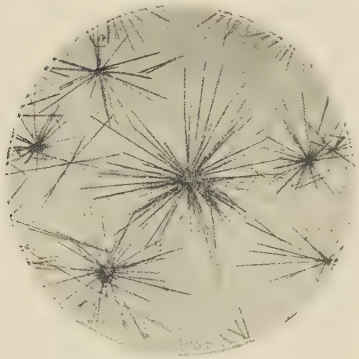


Fig. 466.—Microchemical Gypsum.

This is by far the most sensitive reaction known for calcium, as also for sulphuric acid.

Magnesium.—A rare mineral belonging to the hemimorphite class in the orthorhombic system (p. 65) is struvite, $NH_4MgPO_4 . 6H_2O$. The typical form of this mineral is shown in Fig. 467, which represents one of the crystals from Hamburg, to be seen in most mineral collections. If to a drop of dilute solution of a magnesium salt containing sal-ammoniac and ammonia a drop of sodium phosphate be added, typical struvite crystals soon separate (Fig. 468). They come down most readily in a warm solution.

Fig. 467.

Ammonium.—The same test is used for the detection of ammonium.

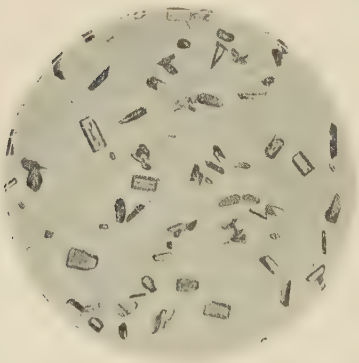


Fig. 468.—Microchemical Struvite.

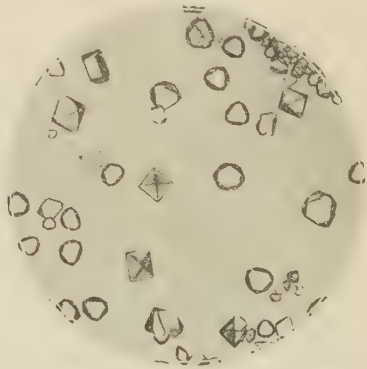


Fig. 469.—Microchemical Cæsium-alum.

To the solution of the ammonium salt a drop of sodium phosphate, one of soda, and one of magnesium sulphate are added in succession. Struvite crystals, as before, come down on warming. This precipitate may also be used as a test for phosphoric acid.

Aluminium.—Solutions of aluminium salts in sulphuric acid give, with cæsium sulphate, colourless isotropic octahedra of cæsium-alum (Fig. 469).

Cæsium is detected by the same reaction when aluminium sulphate is added to a solution of a cæsium salt.

Sodium.—Uranyl acetate gives with sodium salts yellow isotropic

tetrahedra of a uranyl-sodium acetate (Fig. 470). Care must be taken that the reagent is itself free from sodium, which is easily detected by the spectroscope.

Uranium is detected by the same reaction. A solution in nitric acid is saturated with soda and treated with acetic acid.

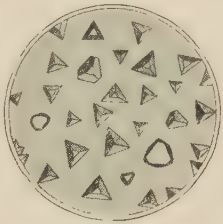


Fig. 470.—Microchemical Uranyl-sodium Acetate.

Silicon.—Silicates are to be decomposed with hydrofluoric and sulphuric acids in a covered platinum dish ; some of the silicon fluoride given off is collected in a drop of water on the under side of the cover. The addition of a sodium salt to this gives faintly rose-coloured hexagonal plates of sodium fluosilicate, Na_2SiF_6.

Potassium is detected by the yellow octahedra of potassium chloroplatinate, K_2PtCl_6, produced on addition of a drop of solution of platinum tetrachloride to dilute solutions of potassium salts in hydrochloric acid.

Similar characteristic reactions can be employed for a number of other elements, but for most of them one of the ordinary blowpipe- or solution-reactions is equally easily and quickly applied. Thus it is unnecessary to resort to a microchemical test for lead or copper, since these metals are so easily recognised by reduction on charcoal.

It is only when the amount of available material is excessively minute that the observer is driven to rely entirely upon microchemical tests ; and then many of his experiments will be simply the solution-reactions indicated above, or similar reactions, modified in such a way as to be applied on a very small scale under the microscope.

For example a minute trace of chloride in a drop of dilute solution can be detected by the production, with silver nitrate, of a white precipitate soluble in ammonia ; the microscope further shows that the precipitate of silver chloride is redeposited from the ammoniacal solution in colourless isotropic octahedra.

(*c*) Spectroscopic Examination

Flame- and Spark-Spectra.—The most delicate of all tests for elements which are only present in traces is, of course, the spectrum which some of them give when a volatile compound containing the element is heated in the flame of a Bunsen burner.

A small fragment of the mineral moistened with hydrochloric acid, or mixed with ammonium fluoride and sulphuric acid, is brought on the end of a clean platinum wire into the edge of the flame, which is then observed with a small direct-vision spectroscope.

The following elements may be at once detected if the compound is at all pure :

Sodium by its brilliant yellow line.

Lithium by two lines, one a weak yellow, and the other a bright red.

Cæsium by two characteristic bright blue lines, and a double line in the orange.
Rubidium by two characteristic violet lines, and by two in the red (which must not be confused with the potassium line).
Potassium by a characteristic line in the extreme red and one in the extreme violet.
Thallium by a single brilliant green line.
Calcium by a brilliant green line and a brilliant orange line.
Strontium by a blue line and a series of brilliant lines in the red and orange.
Barium by a series of brilliant green and red lines.
Indium by a characteristic blue and a faint violet line.

These lines are all very characteristic, but since minerals are scarcely ever pure simple compounds they may contain several of the above and other elements together, so that the spectra yielded by the minerals may be complicated and different elements may mask each other. The spectroscopic test is therefore best applied to the comparatively pure precipitates or solutions obtained in the chemical examination of the mineral rather than to the mineral itself; it is of incomparable value in detecting minute traces of these (and, in skilful hands, of many other) elements.

Very interesting and characteristic spectra are also obtained by subjecting small fragments of most conducting minerals to the electric spark discharge.

Absorption Spectra.—Some minerals, when examined at ordinary temperatures with the spectroscope by transmitted light, show dark absorption bands due to the elements which they contain.

Many of the minerals containing didymium, for example, show broad dark bands in the red and green which are characteristic of that element (parisite, bastnäsite, monazite).

In many cases the bands can even be seen by simply allowing direct

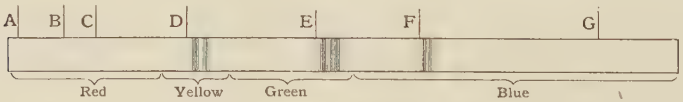


Fig 471.—Absorption Spectrum of Monazite.

sunlight to fall upon the specimen and viewing it with the spectroscope; the reflected light will have penetrated sufficiently far into the mineral to show the absorption spectrum. Thus crystals of monazite, $(Ce, La, Di)PO_4$, can be at once recognised by mere inspection with the spectroscope. If one of the specimens from the Binnenthal, for example, on which isolated crystals of monazite are associated with anatase upon quartz and albite, be viewed through a spectroscope in direct sunlight, the characteristic didymium bands flash into the spectrum the instant a crystal of monazite comes opposite to the slit (Fig. 471).

The mineral rhabdophane, which was formerly supposed to be blende, was discovered in this way and was named from this property.

If a very small fragment of the mineral is to be examined it will be found advisable to place it on the stage of a microscope and focus the direct

rays of the sun upon it by means of the substage condenser ; the eye-piece may then be removed and replaced by the direct-vision spectroscope.

Such absorption spectra are especially characteristic of the metals of the Ce, La, Di group.

Two quite common minerals also show characteristic absorption spectra, namely, zircon and the variety of garnet known as almandine.

Fig. 472 represents the absorption spectrum of zircon.

Fig. 472.—Absorption Spectrum of Zircon.

Fig. 473 represents the absorption spectrum of almandine.

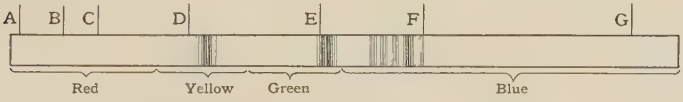


Fig. 473.—Absorption Spectrum of Almandine.

This test is especially useful in the case of gem stones, since it may be applied without the necessity of sacrificing any of the material or even of unmounting the stone. A clue to the composition may thus be obtained by merely looking at the stone through a spectroscope.

It must be remembered that, like all the directional properties, the absorption spectrum is different for rays which vibrate in different directions within the crystal. This may be very easily seen by placing a minute crystal of the hexagonal mineral parisite (a carbonate and fluoride of Ce, La, Di, and Ca) lengthwise under the microscope, and allowing the incident light to pass through the polariser.

When the axis of the crystal is parallel to the longer diagonal of the polariser, the spectrum due to the ordinary rays is that shown in Fig. 474.

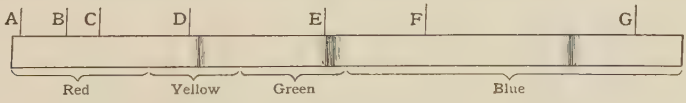


Fig. 474.—Absorption Spectrum of Ordinary Ray in Parisite.

When the crystal is turned through 90° the spectrum is that of the extraordinary rays, Fig. 475.

Fig. 475.—Absorption Spectrum of Extraordinary Ray in Parisite.

The changes which the spectrum undergoes with a change of the vibration-direction are, like the spectrum itself, characteristic of the substance.

Throughout the whole process of testing a mineral it must be remembered, especially with the delicate tests of the flame-reactions and of the spectroscope, that the effects produced may be due not to the mineral itself but to other substances enclosed in it. Nothing can therefore be more important than to ascertain first, by means of the microscope, the purity of the specimen and the nature of any enclosed mineral, and if possible to remove the latter either by picking it out under the microscope from the crushed material or by separation by means of a heavy liquid, if the two minerals differ in specific gravity, or in some cases by the electromagnetic or electrostatic methods.

Further, the reactions may be partly due to a slight intermixture of an isomorphous compound which cannot be seen or separated by any mechanical process, since it is present as one of the constituents of an isomorphous mixture.

For the chemical identification of a mineral, attention must be paid rather to its main constituents than to those which it contains as mere traces, and this fact robs the spectroscopic tests of some of their value in practice.

Some well-known minerals possess such characteristic properties that they may be recognised at once.

If powerfully magnetic, the specimen is almost certainly magnetite ; for except native iron, which is exceedingly rare, the only other markedly magnetic minerals are pyrrhotite and platinum, and these are only weakly so in comparison with magnetite. Ilmenite is slightly magnetic.

Again, rock-salt is at once recognisable by its taste ; the astringent taste of the alums and of the sulphates of iron and of copper, and the bitter taste of epsomite are also characteristic. Only minerals which are soluble in water possess a taste.

No minerals have in themselves a smell sufficient to distinguish them, but the hydrated silicates of alumina belonging to the family of the clays emit a characteristic earthy smell when breathed upon ; and some minerals which contain sulphur or arsenic emit a sulphurous or arsenical (" alliaceous ") smell when struck with a hammer.

Some clays and allied minerals adhere to the tongue when touched with it ; this property affords a rough method of distinguishing between steatite and lithomarge, of which only the latter adheres to the tongue. One variety of halloysite possesses this property in so marked a degree that it has been named " glossecollite."

The remarkable greasy feel of steatite is also of some value in its recognition.

Many copper compounds are blue or green ; most uranium compounds are brilliant green or yellow.

A useful hint is often supplied by the minerals with which the doubtful material is associated or by its products of decomposition ; green malachite or blue chessylite, for example, encrusting the mineral, indicate copper, while the apple-green of nickel- or the rose-red of cobalt- compounds may often be detected on the decomposed surface of a mineral containing one of these elements.

PART II

DESCRIPTION OF THE MORE IMPORTANT MINERAL SPECIES

SECTION I

THE ELEMENTS

DIAMOND, GRAPHITE

Diamond.[1]—Carbon, C. Cubic; symmetry, di-tesseral polar (?). Common form, octahedron (supplementary twin of tetrahedra ?). Also twinned on (111). Cleavage {111}, perfect. Brittle. Fracture, conchoidal. H = 10; G = 3·52. Colourless. Lustre, adamantine. Transparent. Refraction very strong; $\mu = 2{\cdot}417$(Na). Dispersion very strong. Infusible. Insoluble in acids.

With the above description compare crystals from **Kimberley** (South Africa).

Diamond (Germ. and Fr., *Diamant*), the hardest and most valuable of minerals, is naturally the one which excites the greatest popular interest;

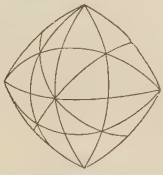


Fig. 476.—Diamond. Curved Octahedron.

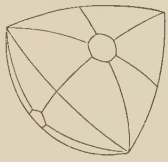


Fig. 477.—Diamond. Curved six-faced Tetrahedron, with {111}.

its value results mainly from the extraordinary hardness and the brilliancy which together make it the most precious of gems; and these characteristics have been known from very early times. The modern scientific interest of the diamond has mainly centred round the vexed question of its origin in Nature, and the attempts to reproduce it by artificial means; but, as will presently be shown, it has been the subject of much scientific investigation in other respects.

Diamond is practically unknown except as crystals (unless in the form of boart or carbonado), and is generally found (in river gravels, sands and conglomerates, and in the South African "blue ground")

[1] The short description at the head of each species gives the principal characters of typical specimens, and a locality by which they are illustrated is in each case cited; many of these characters (*e.g.* specific gravity, colour, optical properties) may differ considerably with varying chemical composition. The terms "fusible" or "infusible" refer to the mouth blowpipe, and numbers following in brackets to the scale of fusibility (*cf.* p. 328).

as isolated individuals. These usually appear to be simple octahedra, sometimes smooth and sharp, but often curved (Fig. 476); other forms are known, such as the dodecahedron, and, more rarely, the cube. It used to be supposed that the Indian diamonds were mostly octahedral, and that the other two forms were characteristic of the Brazilian crystals; this is not really the case; among the South African diamonds many different forms have been found. A remarkable and characteristic feature is the curvature of the faces; owing to this peculiarity some of the small crystals appear almost like drops of gum. So far as is known from experiments, the curvature of crystal faces is generally due to the action of a solvent, and many diamond crystals present other features which may also be the result of corrosion; the cube is one of the rarest forms of diamond, and when present the cube-faces are rough and drusy (Fig. 480); again the octahedron-faces themselves, though sometimes smooth and brilliant, are often covered with the most beautifully regular triangular markings (shallow pits) which have the appearance of etched

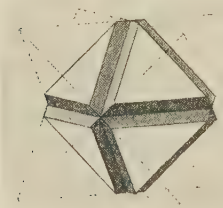


Fig. 478.—Diamond. Supplementary Twin of Tetrahedra.

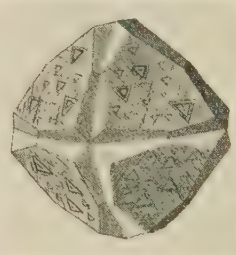


Fig. 479.—Diamond. Supplementary Twin, showing etching figures.

figures. These are the same upon all the eight faces of the octahedron, but they do not for that reason necessarily indicate that the crystal is holosymmetric, *cf.* Fig. 287, p. 128. Many octahedra of diamond have a groove or furrow in the place of each octahedron-edge (Fig. 478), and if these re-entrant angles indicate twinning, the crystals must in reality belong to the tetrahedrite class (di-tesseral polar).

Much controversy has taken place upon the question whether the diamond is holosymmetric, as indicated by the common octahedral form, or tetrahedral, as is suggested by the grooves.

On the one hand crystals have been found which are undoubtedly simple crystals of tetrahedral habit; Fig. 477 represents a crystal which is simply the six-faced tetrahedron of Fig. 106 (p. 51) but with curved faces; and all the various peculiarities of form may be explained by the supplementary twinning of such crystals.

In a supplementary twin of two tetrahedra (twinned by reflection in a cube-plane) let the projecting corners be truncated by faces of the inverse tetrahedron, as in Fig. 478. The twin-crystal then presents the appearance of an octahedron with grooved edges, and it will be observed that the faces of this apparent octahedron all belong to the same form, and

would all present the same corrosion-figures if etched. Now if the interpenetrating crystals have faces of a six-faced tetrahedron like Fig. 477, the resulting crystal will be an octahedron with curved grooves resembling Fig. 479. This is a characteristic, if rare, form of diamond. Other curved and grooved crystals, such as the rounded cube of Fig. 480, can be explained as due to the same supplementary twinning.

On the other hand, very careful experiments have failed to reveal any trace of pyroelectric properties, such as might be expected in a crystal with polar symmetry; and the furrows above referred to have been attributed to irregularities of growth or to corrosion.

The symmetry of the structure as revealed by X-rays (see p. 291) is holosymmetric; but this does not necessarily prove that the crystals belong to the holosymmetric class, as other cases are known where the faces of a crystal conform to a lower degree of symmetry than that indicated by the X-ray determinations (*e.g.* in sylvite and cuprite, p. 296).

The twin-growth above mentioned (Fig. 478), which may be geometrically described as due to reflection over a cube-face (100), is not the only twinning known in diamond. "Spinel twins" of octahedra (p. 99) united

Fig. 480.—Diamond. Supplementary Twin; Cubic habit.

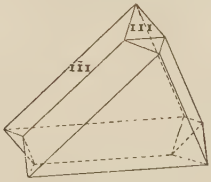


Fig. 481.—Diamond. Spinel Twin.

along (111), as in Fig. 481, are by no means rare; they are known to the Amsterdam jewellers by the name of *naadsteenen* (Dutch) or *Naht-steine* (German), in allusion to the suture-line or twin-junction of the two crystals. These twins, as is the case with the twin-crystals of many other substances, are flattened along the composition-plane.

Only in the latter twins is the perfect octahedral cleavage interrupted by a re-entrant angle; the supplementary twins cleave like single individuals, since the faces of {111} are parallel throughout.

The perfect cleavage is of great use to the diamond-cutters, since it enables them to chip away projecting corners and inferior parts of the stones, without incurring the labour of grinding them away: the labour of grinding facets upon a diamond is very great on account of the extreme hardness of the mineral. The diamond is, in fact, the hardest substance known, and can be easily distinguished from all other minerals by this property; it is for this reason one of the most potent cutting, grinding, and polishing agents, and can itself be polished only by diamond powder; it is used as the cutting point in the determination of the hardness of other minerals by means of the sclerometer (p. 123). Metal discs charged with diamond dust are generally used for cutting thin sections of rocks and other hard substances for the microscope, and the same material is used in the

working and polishing of most hard ornamental stones. Diamond is also used for the cutting points of drills for rock-boring purposes, and also for trueing and shaping emery wheels. In the diamonds used by glass-cutters the cutting portion is usually the curved edge between two curved faces or between a natural curved face and a cleavage-plane; its efficiency is said to be due to the curvature, which prevents more than one point of the cutting edge from being in contact with the glass. Perforated plates of diamond (especially the flattened spinel twins) are sometimes used in wire-drawing. As is probably the case in any crystal, the hardness is different on the faces of different forms, being greater upon the cube- than upon the octahedron-face. Different specimens of diamond also differ somewhat in hardness, and the Australian and Borneo stones are reputed to be the hardest.

The hardness and consequent durability of the diamond confer upon this mineral much of its value as a gem stone. Other minerals (titanite, for example) possess optical properties which would render them valuable as gems, were they not too soft, whereas diamond is practically indestructible by friction; it is, further, unaffected by acids.

The indestructibility of the diamond was well known to the ancients, and accounts for the Greek name ἀδάμας ("the invincible"), of which the modern names adamant, diamant, diamond, are corruptions. It is certain that the ἀδάμας of Greek authors does not always refer to the diamond; but in the *Historia Naturalis* of Pliny, at any rate, there is a detailed description of the stone which mentions its hardness and resistance to fire, and leaves no doubt in the identification. Pliny distinguishes six different varieties. Of the Indian diamond he says that it resembles rock-crystal by its transparency, and by its pointed hexagonal termination (*laterum sexangula laevore turbinatus in mucronem*); sometimes, he adds, it appears to be formed by two halves resembling two cones united by their base. In this description we may perhaps recognise one of the twinned forms.

By Pliny and by many ancient and mediæval writers the hardness was confused with toughness, and it was stated that the diamond resists all attempts to break it, so that if laid upon an anvil and struck with a hammer both anvil and hammer will fly to pieces before the diamond is broken. According to Bauer, the diamond hunters have been under the same delusion, and have broken many fine stones in applying this as a test. The tales about the indestructibility of the diamond were, however, rejected by Böetius de Boot in his book on stones published in 1609.

The diamond was also believed to be incombustible, until experiments made by the Florentine Academicians in 1694 proved that it could be burnt, either in the furnace or by the concentration of the sun's rays. Newton had previously asserted that the high refractive power of the diamond indicated that it must be a combustible substance.

Subsequent experiments, especially those of Davy (1816) and Krause (1890), have proved not only that diamond can be burnt in the air, but that the only product of combustion is carbon dioxide, and therefore that diamond is pure carbon.

A fragment of diamond can, with some difficulty, be consumed slowly by heating on platinum foil before the blowpipe—but it requires a temperature of about 900° C.

Out of contact with air diamond may be raised to a much higher temperature (about 1500° C.) without alteration; but above 1900° it is converted rapidly into graphite.

Although the diamond is usually colourless, yellow crystals are common, especially from South Africa; blue, green, and red are rare colours, and consequently add much to the value of the stone.

When coloured diamonds are heated they do not lose their colour, although it is sometimes altered; this indicates that the colour is not due to hydrocarbons, as has been supposed, but probably to metallic oxides.

The lustre is adamantine, or often somewhat greasy. Like all substances of adamantine lustre, the diamond possesses a very high refractive index (2·417), which is quite enough to distinguish it from all artificial imitations made of glass, since their index is not above 1·8. Other minerals which have a higher refractive power than the diamond, such as cuprite (2·85), cinnabar (3·02), proustite (2·94), crocoite (2·42), anatase (2·55), rutile (2·76), are coloured and far less transparent. Owing to this high index any rays within a diamond which meet the surface at angles of incidence greater than $24\frac{1}{2}°$ are totally reflected, so that most of the light which enters a well-facetted stone emerges again on the same side after internal reflections, and this gives the gem its extraordinary lustre. This result is admirably attained by the "brilliant" mode of facetting which is reputed to have been the discovery of Cardinal Mazarin. The dispersion (0·063 between the lines A and H) is greater than that of all other precious stones except titanite. To this are due the brilliant colours ("fire") of the light refracted by a facetted diamond.

Some diamonds are said to be perfectly isotropic, but most exhibit a weak double refraction, which was attributed by Brewster to internal strain, since it is most noticeable in the neighbourhood of cavities; he supposed this to prove that the diamond had once been sufficiently soft to be compressible by the gases confined in these cavities.

The birefringence is, however, not confined to the neighbourhood of inclusions, and it is possible that the diamond is really pseudo-cubic, as was supposed by Mallard; or, more probably, the birefringence may be due to strain, resulting either from external pressure when the diamond was formed or from contraction when cooling.

Friedel has recently found evidence that, on heating, the diamond undergoes a polymorphous change at 1885° C. into a different modification, which may possibly be also cubic, and which above that temperature is rapidly converted into graphite; and he attributes the birefringence to strain caused by a change of volume accompanying this transformation as the diamond cooled but while it was still hot enough to be more or less plastic.

The existence of strain in some cases is shown by the fact that some diamonds are apt to fly to pieces when taken out of the ground.

A remarkable optical property of the diamond is its phosphorescence; most specimens can be easily made to emit light by friction upon wood, and they phosphoresce most beautifully when submitted to the electric discharge in a vacuum tube. It has been observed that the light emitted by the cube-faces is different from that emitted by the octahedron-faces.

Diamond is remarkably transparent to X-rays—a character readily distinguishing it from glass imitations, which are opaque to these rays.

Two other remarkable forms of carbon are generally regarded as varieties of diamond. *Boart* is a crystalline translucent substance, generally rather grey in colour, and with a curved drusy surface; sometimes a single stone consists of diamond in one part and of boart in another. The true boart of Brazil has a radial-fibrous structure, and is much prized for use in rock drills. The name boart, however, is often used to denote those inferior crystals and fragments of diamond which are not fit for gem stones.

Carbonado is a still harder and more compact substance; it is a dull black opaque material, somewhat porous, so that it resembles charcoal in appearance, and is absolutely devoid of cleavage; it is actually somewhat harder than the diamond itself; owing to these qualities it is of the greatest value for rock drills.

Carbonado is only found in the diamond deposits of Bahia (Brazil), in angular fragments which sometimes display a rude crystalline (cubic) form.

In India, Brazil, Borneo, and other parts of the world, diamonds are to be found in river sands and gravels, where they may have survived the friction of ages owing to their superior hardness, but their occurrence in such secondary deposits throws no light upon the real origin of the mineral. In South Africa, however, where they were also originally found in gravels of the Vaal river (the "river diggings"), they were subsequently discovered in far greater quantities in the peculiar deposits known as the "dry diggings" described below.

Among the most famous diamonds may be mentioned the Koh-i-Nur, which weighed 186 carats [1] (about $1\frac{1}{4}$ ozs.) when brought from India, and now, after re-cutting, 106 carats; the Orloff, weighing (cut) 194 carats, which was one of the Russian Crown jewels; the Regent or Pitt, weighing (cut) 137 carats, one of the French Crown jewels; the Star of the South, a Brazilian stone, which weighed 254 carats when found; the *green* Dresden diamond, weighing 40 carats, preserved in the Green Vaults at Dresden; the *blue* Hope Diamond (44 carats), probably part of a larger Indian stone which was stolen with other French Crown jewels in 1792; the Tiffany, an *orange-yellow* South African stone, which weighs $125\frac{1}{2}$ carats (cut); and the Excelsior, also from South Africa, which weighed no less than 971 carats (about $6\frac{1}{2}$ ozs.) when found.

By far the largest diamond yet found is the Cullinan, now known as

[1] The weight of one carat varies somewhat in different countries, but is approximately 3·165 grains = ·205 gram; 1 oz. (Troy) = 151·7 carats. Since 1913 the metric carat, equal to ·2 gram (1 oz. = 155·5 carats), has been the legal unit in England.

the Star of Africa, which was found near Pretoria (Transvaal) in 1905. This was a fragment of a perfectly clear, roughly octahedral crystal, partly bounded by a natural cleavage-surface, and weighed 3025¾ carats, or about 1⅓ lb. It was presented to King Edward VII, and has been cut into a number of stones, of which two, of 516 and 309 carats respectively, are the largest brilliants in existence.

A Noteworthy Locality :

Kimberley (South Africa).—In the " dry diggings " diamond occurs as octahedral crystals, often with curved edges (Fig. 476) and somewhat greasy lustre, enclosed in a greenish serpentinous breccia containing grains of red garnet, fragments of various green pyroxenes, glittering scales of an altered magnesia-mica (known as vaalite), and black granules of ilmenite. The dry diggings are vertical pipes of unknown depth, and 200 yards or more in diameter at the surface ; the diamonds are disseminated through the brecciated serpentinous material with which these pipes are filled ; this material is known as " blue ground " and contains fragments of many minerals and rocks. Different opinions have been held concerning the origin of these vast pipes and of the diamonds which are found in them ; it has generally been maintained that the pipes themselves are volcanic and that the blue ground is an altered peridotite (olivine-rock) from which the diamond has crystallised ; and the alteration of the peridotite has been ascribed to hydrothermal action.

That some of the rocks from which the blue ground has been derived may probably be the original matrix of the diamond, is indicated by the fact that small diamonds are said to have been obtained by dissolving graphite in fused olivine, or in a mixture of silicates having the same composition as the blue ground. That the latter is a possible solvent of the diamond has been proved by actually heating diamond in the blue ground, when it becomes corroded, etched, and finally dissolved.

At some of the dry diggings (Transvaal) diamonds have been found in boulders of eclogite (a crystalline rock consisting of pyroxene, garnet, and olivine) embedded in the blue ground ; so that a rock of this kind may probably be one source of the mineral in South Africa.

Graphite.—Carbon, C. Hexagonal ; symmetry, di-hexagonal alternating. Common form, hexagonal plates. Cleavage, basal, perfect. Pliable. H = 1 ; G = 2·2. Iron-black. Streak, grey. Lustre, metallic. Opaque. Infusible. Insoluble in acids.

With the above description compare crystals from **Pargas** (Finland).

Graphite, the other modification of carbon, presents a most marked contrast to diamond ; it is one of the softest, as diamond is one of the hardest, of minerals ; it is a good conductor of electricity, whereas diamond is a non-conductor ; it rarely occurs in crystals, and these are only imperfect hexagonal plates with triangular striations. The crystals from Finland mentioned above occur in a crystalline limestone. Crystals

of graphite have for the most part been found in crystalline schists, gneisses, and limestones. In thin laminæ graphite is pliable; it is greasy to the touch.

The softness of graphite causes it to leave a mark when rubbed on paper, and makes it suitable for pencils, and for polishing grates or for use as a dry lubricant; the name is derived from γράφω, I write. The so-called "black-lead" of Borrowdale in Cumberland has been worked since the sixteenth century; it is a compact graphite which occurs in large quantities associated with basic igneous rocks.

A Noteworthy Locality:

Ceylon.—Vast quantities of graphite are mined in Ceylon, where it fills true veins in the granulite and associated rocks; the graphite sometimes has a columnar structure transverse to the vein, but where the rocks have been disturbed the soft graphite has been crushed and contorted, and is sometimes reduced to a scaly mass.

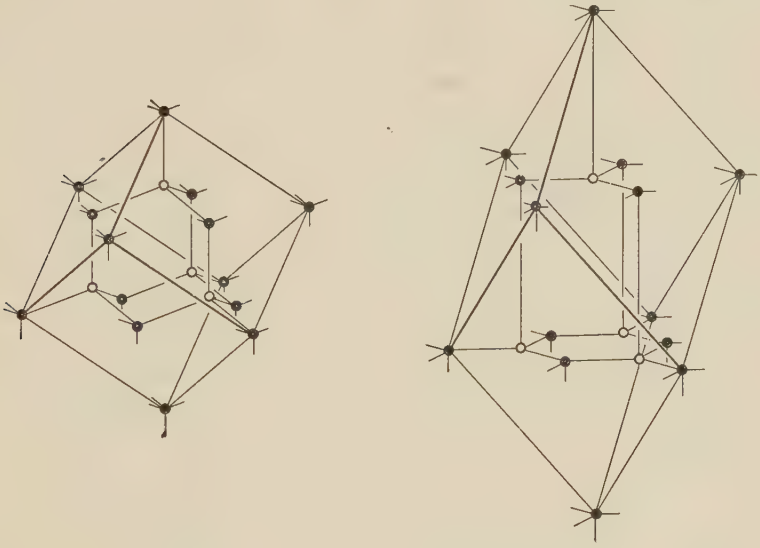
The specific heat of diamond (0·12) at ordinary temperatures is less than that of graphite (0·18), but in both minerals it increases rapidly with rise of temperature and becomes nearly equal (about 0·46) at 980° C.

Diamond is not converted into graphite by ordinary combustion, but it is transformed into a mass of graphite scales when heated in the electric arc; it is also blackened when subjected to electric bombardment in a vacuum tube, and this is probably due to a superficial alteration into graphite.

Many attempts have been made to effect the reverse change and convert other forms of carbon into diamond, mostly without success. Graphite itself is often obtained as an artificial product; for example, in iron works, as crystalline scales separated by the blast from molten iron which contains carbon, or as segregations in the preparation of carborundum. It has long been known that graphitic nodules are by no means rare in meteoric iron; from some meteorites have been extracted *cubic crystals* of graphitic carbon (cliftonite), which have been regarded as altered diamond; and some meteorites, conspicuously one mass of iron found at Cañon Diablo in Arizona, have been stated to yield actual diamond crystals of appreciable size. In the experiments of Moissan on the artificial production of diamond, iron was used as the solvent. Pure carbon was dissolved in soft iron fused in the electric furnace, and the mass was cooled suddenly by immersion in water, or in a bath of melted lead. A solid crust was thus formed; and since iron expands in solidifying, the central portion of the mass was subjected to very high pressure. It was claimed by Moissan that under these conditions the dissolved carbon crystallised out as minute octahedra and tetrahedra of diamond.

It is interesting to compare the structure of graphite, as revealed by X-rays, with that of diamond (p. 291). According to Debye and Scherrer, the structure resembles that of diamond in consisting of two similar lattices with centred faces, ● and ○, interpenetrating; but the unit cell of graphite is a *rhombohedron* with centred faces, which would be obtained by

extending the cubic cell along one of its diagonals, which becomes the principal axis of the hexagonal crystal. If this axis be set vertical, the atoms of the second constituent lattice will lie vertically below those of the first, at a distance which is probably one-third of the long diagonal,—instead of one quarter, as in diamond. This arrangement is shown in Fig. 482, in which the unit cells of graphite and diamond are represented on



Diamond. Graphite.

Fig. 482.—Structure of Diamond and Graphite.

the same scale. In graphite the atoms of both lattices lie in the same horizontal planes, and the structure consists of a series of equidistant horizontal planes, closely beset with carbon atoms (forming a bee's-cell pattern like Fig. 414), and relatively distant from one another. This may well account for the perfect basal cleavage of graphite, and the toughness and smoothness of the cleavage-laminæ.

SULPHUR

Sulphur.—S. Orthorhombic ; symmetry, holoaxial.

$$a : b : c = 0{\cdot}813 : 1 : 1{\cdot}903.$$

P = {111}, p = {1$\bar{1}$1}, S = {113}, s = {1$\bar{1}$3}, n = {011}, C = {001}, e = {101}.

$$P\!p\ (111) : (1\bar{1}1) = 73^\circ\ 34', \quad PC\ (111) : (001) = 71^\circ\ 40',$$
$$e\mathrm{C}\ (101) : (001) = 66^\circ\ 52'.$$

Common form, a bipyramid. Cleavage {001}, {110}, very imperfect. Brittle. Fracture, conchoidal. H = 2 ; G = 2·07. Sulphur-yellow. Streak, white. Lustre, resinous-adamantine. Transparent. Refraction very strong ; $\gamma = 2{\cdot}24$, $\beta = 2{\cdot}04$. Birefringence very strong, positive ; $\gamma - \alpha = 0{\cdot}29$. Axial plane (010). Acute

bisectrix perpendicular to C. $2V = 69°$. $\rho < v$. Easily fusible, at 108° C. Volatilises and burns. Insoluble in acids.

With the above description compare crystals from **Girgenti** (Sicily).

Sulphur (Germ. *Schwefel*, Fr. *soufre*, Span. *azufre*) is found in large and beautiful crystals at Girgenti in Sicily. These are generally the rhombic bipyramids of Fig. 485 ; but on some specimens the crystals are markedly sphenoidal in habit, and it is therefore nearly certain that the mineral belongs in reality to the holoaxial class. Fig. 483 represents such a crystal ; and even in Fig. 485 P is slightly larger than *p*, but it has not been possible to find any certain external difference between the faces P {111} and *p* {1$\bar{1}$1}. Twinning, though rare, is known according to no less than four different laws : namely by reflection over (101), (011), (110), and (111). Fig. 484 represents a crystal from the Solfatara of Cattolica in Sicily, twinned thus by juxtaposition on (1$\bar{1}$0) : the other twins are generally more or less interpenetrant, sometimes even cruciform. In addition to its strong refraction and birefringence, sulphur possesses another

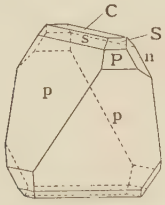


Fig. 483.—Sulphur. Sphenoidal Habit ; P {111}, S {113}, *p* {1$\bar{1}$1}, *s* {1$\bar{1}$3}, *n* {011}, C {001}.

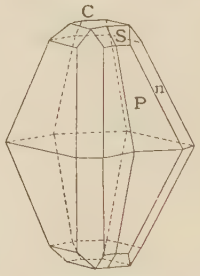


Fig. 484.—Sulphur, twinned on (1$\bar{1}$0).

remarkable optical peculiarity ; the angle between the primary optic axes is 72° 20′, and that between the secondary optic axes is 64° 57′ ; so that the angle between a primary and a secondary optic axis, which in most minerals is only a few minutes, is in sulphur 3° 42′.

The heat-conductivity of sulphur is so low that the warmth of the fingers is sufficient to cause a crystal to crack if it be incautiously handled ; and if it be held in the hand close to the ear a crackling sound may be heard from the same cause.

The best and largest crystals of sulphur are not those which have been formed by sublimation from sulphur vapours in volcanic regions, but are found (as in Sicily) in marl or clay associated with such minerals as calcite, aragonite, gypsum, and celestite, where they appear to have been deposited from hot waters. The sublimation-deposits usually occur as incrustations. In metallic veins sulphur may occur as a result of the decomposition of sulphides. Owing to the variety of its modes of origin, sulphur is found in many forms ; very commonly as reniform, irregular, or earthy masses ; while the colour, especially of the earthy varieties, may be orange, brown, or grey.

Sulphur is polymorphous ; when fused and allowed to crystallise

from the molten state it assumes an entirely different form belonging to the monoclinic system ; this modification has rarely (perhaps never) been found as a mineral ; it readily passes into the orthorhombic modification, which is the more stable at ordinary temperatures ; in fact the artificial monoclinic crystals generally become dull and brittle after a time, through their spontaneous conversion into an aggregate of minute orthorhombic bipyramids. The orthorhombic crystals may be obtained artificially by allowing sulphur to crystallise at the ordinary temperature from a solution in carbon disulphide.

In addition to these two, no less than three or possibly four other modifications of sulphur have been obtained.

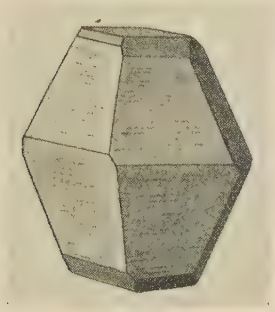


Fig. 485.—Sulphur. Usual Habit.

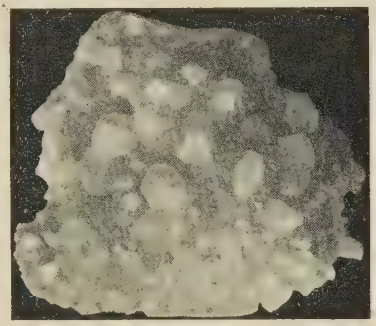


Fig. 486.—Sulphur from Girgenti (British Museum).

Sulphur is distinguished from all other minerals by easily burning with the production of acid vapours of pungent odour (SO_2).

A Noteworthy Locality :

Girgenti (Sicily).—Beautiful crystals (Fig. 486), usually bipyramids {111} with {113} and {001} ; more rarely of tetrahedral habit, accompanied by crystals or crystalline crusts of white celestite ; the latter is either in prisms or in acute pyramids. The best specimens are from Roccalmuto and Cattolica ; the sulphur is not a sublimation-product of volcanic origin, but occurs in beds of a calcareous marl in the nummulitic limestone.

THE ARSENIC GROUP

Arsenic.—As. Hexagonal; symmetry, di-hexagonal-alternating (calcite class). (100) : (010) = 94° 54′. Cleavage {111}, perfect ; {110}, imperfect. Brittle, slightly sectile. Fracture, uneven. H = 3½ ; G = 5·7. Colour and streak, tin-white, tarnishing to grey. Lustre, sub-metallic. Opaque. Volatilises without fusion. Oxidised by nitric acid.

With the above description compare crystalline material from **Schneeberg** (Saxony).

Antimony.—Sb. Hexagonal ; symmetry, di-hexagonal-alternating (calcite class). (100) : (010) = 92° 53′. Cleavage {111}, perfect ; {110}, fair ; {11$\bar{1}$},

imperfect. Brittle. Fracture, uneven. H = 3½; G = 6·6. Colour and streak, tin-white. Lustre, metallic. Opaque. Easily fusible. Volatilises. Oxidised by nitric acid.

With the above description compare crystalline material from **Andreasberg** (Harz).

Bismuth.—Bi. Hexagonal; symmetry, di-hexagonal-alternating (calcite class). (100) : (010) = 92° 20′. Cleavage {111}, perfect; {11$\bar{1}$}, fair. Sectile. Fracture, crystalline. H = 2½; G = 9·8. Silver-white (reddish). Streak, grey. Lustre, metallic. Opaque. Easily fusible. Volatilises. Soluble in nitric acid.

With the above description compare crystalline material from **Schneeberg** (Saxony).

Arsenic, antimony, and **bismuth,** three minerals which generally occur only as crystalline granular masses or botryoidal and curvilaminar crusts, constitute an isomorphous group of rhombohedral elements which are allied to the non-metal sulphur in some of their properties, and to the metals proper in others. They may be regarded as a transitional group leading to the metals.

They may be recognised by their metallic appearance and granular structure, and by the brilliant basal cleavage. The secondary, rhombohedral cleavages given above may be due to separation along planes of twinning.

Native arsenic and antimony are of considerable commercial importance as sources of these metals. Native antimony generally contains arsenic; the name allemontite is given to a mixture containing about 60 per cent of arsenic. Beautifully tarnished crystals of bismuth, resembling skeletal cubes (the angle of {100} in this group is very nearly a right angle) are formed from fusion during the manufacture of this metal.

THE GOLD GROUP

Gold.—Au. Cubic, holosymmetric. Common form, elongated octahedron. Malleable; ductile. Fracture, hackly. H 2½; G = 19·3. Colour, gold-yellow. Lustre, metallic. Opaque. Fusible at 1200° C. Insoluble in acids, except *aqua regia*.

With the above description compare crystallised groups from **California**.

Gold (Fr. *or*, Ital. *oro*), like diamond, has always been one of the most familiar minerals on account of its value; and the value of gold, like that of diamond, is due not only to the rarity, but also to the durability of the metal; it further resembles diamond in the fact that its chief scientific interest to the mineralogist results from the mystery that surrounds the origin of this metal. On the other hand, whereas attempts to reproduce diamond are only modern, the attempts to reproduce gold date from very early times, and have been abandoned since the failures of the alchemists of the Middle Ages, to whom it was a fascinating problem. Again, unlike diamond, gold is durable not by virtue of hardness but only because it resists the action of solvents. For this reason gold ornaments belonging to the very earliest periods have been preserved. Cloisonné work found in Egypt dates from the twelfth dynasty (2500 B.C. ?), and the

beautiful gold ornaments recently found in Mesopotamia are much earlier (before 3000 B.C.).

Although the largest masses of gold have been found as nuggets in the gravels and sands which have been so fruitful a source of the precious minerals, it is very seldom under these conditions found crystallised. Well-defined crystals are altogether rare, but they are sometimes found in metalliferous veins, or where the gold occurs in quartz "reefs," as in Hungary, Russia, Australia, Brazil, and California. Crystals from Transylvania in particular have been carefully studied; among them are sharply-defined cubes and cubo-octahedra, but they are very often rod-shaped and elongated along the edge in which cube- and octahedron-faces intersect, or they are platy and flattened along an octahedron-face. Such rods and plates, being united by twinning on (111), give rise to remarkable dendritic groups and tessellated surfaces (Fig. 487).

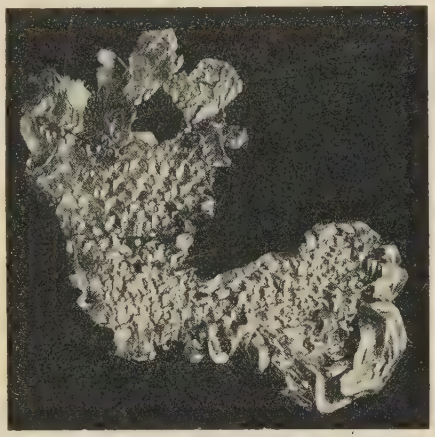


Fig. 487.—Gold. Tessellated Plate from Colombia (British Museum).

Fig. 488 represents the twinning by which vom Rath explained the structure of a reticulated gold group from Hungary. Each member is apparently a rhombic prism of 70° 32′, but is in reality bounded by faces A, $\underline{A}$ of two elongated cubes, extended in the direction of the diagonal of one of the cube-faces, modified by faces e $\underline{e}$ of {210}, and twinned together on an octahedron-face, which is parallel to the plane of the paper. The two crystals are united along the twin-plane and interpenetrate. The cube-faces are striated parallel to their intersections with e. The side branches are composed of parts of the same two individuals, twinned upon the same octahedron-face, but elongated along the diagonals of other faces of the cube.

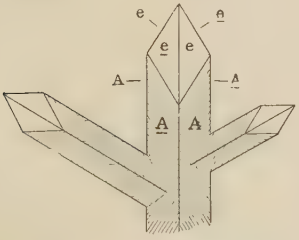


Fig. 488.—Gold. Twin-Group; A {100}, e {210}.

Twinning upon the octahedron, and the misshapen aspect due to elongation of the crystals, or to flattening along the octahedron-face, suffice to explain all the most fantastic and complicated forms of gold; some of these present the appearance of hexagonal pyramids or monoclinic plates, and have even been described as such, but there is no reason to believe that gold is anything but cubic and holosymmetric. Faces of $\{hk0\}$ and $\{hkk\}$ can often be distinguished in addition to cube, octahedron, and dodecahedron, but the crystals are usually rounded, curved, or uneven, and consequently

difficult to decipher. The rounding of the edges is not due to fusion, although gold sometimes presents quite the appearance of fused crystals.

The structure of gold crystals is that of the face-centred cubic lattice, the length of the cube-edge being $4{\cdot}08 \times 10^{-8}$ cm.

The metal is fusible at about 1200° C., and (like silver) melts to such perfectly spherical globules that a microscopical measurement of the dimensions of the button obtained in an assay may be employed as a measure of the amount of gold contained in the sample, in place of weighing.

All native gold contains more or less silver, and those specimens which contain most silver are palest in colour, and are also the hardest and the least dense; with only 10 per cent of silver the specific gravity is as low as 17·7. The purest native gold is said to be that of Mount Morgan in Queensland (99·7 per cent Au). Most of the Hungarian gold contains about 30 per cent of silver. Since the time of Pliny such argentiferous varieties of gold have been called "electrum" (*ubicunque quinta argenti portio est, electrum vocatur*). The name electrum originally signified amber, and was no doubt applied to gold on account of its colour. The crystals of Hungarian electrum are among the sharpest and best, and this variety must be regarded as an isomorphous mixture of the two metals.

It is only necessary here to allude briefly to the various modes of occurrence of gold and the theories relating to its origin, so far as they are connected with the properties of the metal.

In addition to the nuggets, grains, and scales of gold which are found in sands and gravels of secondary origin ("placer deposits"), and have clearly not been formed at the spot where they are now found, there are four well-defined types of gold deposits:—(1) Metalliferous veins, which contain gold enclosed in, or accompanying, metallic sulphides, especially iron-pyrites; (2) quartz reefs, which are veins or masses of quartz containing gold in the metallic state disseminated through the quartz; auriferous sulphides also accompany the quartz reefs; it is from such deposits that many of the crystallised specimens to be seen in museums are derived; (3) the "banket" formation of the South African gold-fields, which is a quartz conglomerate rich in gold so finely disseminated as to be for the most part invisible; (4) the siliceous sinter of Mount Morgan in Queensland, a ferruginous sinter which is richly impregnated with the metal.

In the last three types of deposit the gold is generally supposed to have been introduced by percolating solutions simultaneously with the silica, and to have been derived from the decomposition of metallic sulphides in which it was originally contained. The outcrop of auriferous lodes generally consists of a cellular ferruginous quartz known as "gossan" (the *eiserner Hut* of the Germans, Fr. *chapeau de fer*), which is filled with hydrates of iron, the decomposition products of iron ores. In the Mount Morgan deposits the gold appears to have been introduced through the agency of heated water; and it is said that gold is being deposited at the present day by the hot waters of the Steamboat Springs in Nevada.

On the other hand, no natural compounds of gold are known except tellurides, and it is not understood in what way the metal can have been

carried in solution, whether as chloride, as has been suggested by some, or as an alkaline aurate, as has been held by others.

The origin of the nuggets found in placer deposits has been the subject of equal controversy, for it has been asserted that they are both larger and purer than any masses of gold found in reefs similar to those from which they might have been derived; consequently it has been supposed that they have not been washed out from the debris of reefs but have grown by accretion in these deposits through the agency of some percolating solution. It has, however, been shown that a gold nugget polished and etched with acids displays a crystalline structure throughout like that of Fig. 4, p. 4, and never a curvilaminar, or onion-like, structure, such as would result from successive layers deposited round a nucleus.

The gold contained in auriferous pyrites is not present as any compound in isomorphous mixture, but as metal disseminated through the crystal. Sometimes in decomposed crystals of pyrites and in the prisms of aikinite from Beresov, in the Urals, there is a nucleus or a rod of gold, which seems to indicate by its shape that the metal has become concentrated by a process of crystallisation within the enclosing crystal during the decomposition of the latter, and it is possible that some such concentration has taken place elsewhere and under other conditions.

In connection with the origin of gold it may be borne in mind that all sea water and many fresh waters contain gold in minute but appreciable quantities; and gold is, in fact, one of the most widely distributed elements.

A Noteworthy Locality:

Verespatak (Transylvania).—Veins which traverse the conglomerates, trachytes, andesites, and dacites of this region have been worked for gold since Roman times. The gold, both crystallised and in mossy, leafy, and wiry forms, accompanies amethyst and quartz, blende, calcite, rhodochrosite, iron pyrites, and other minerals; it is generally of pale colour, and much twinned.

The gold group includes also the metals silver and copper, which are isomorphous, all belonging to the cubic system and having similar structures (the face-centred cubic lattice).

Silver.—Ag. Cubic, holosymmetric. Common form, cubes. Twinned on (111). Malleable; ductile. Fracture, hackly. H = 2½; G = 10·5. Silver-white. Lustre, metallic. Opaque. Fusible at 1050° C. Soluble in nitric acid.

With the above description compare crystallised groups from **Kongsberg** (Norway).

Copper.—Cu. Cubic, holosymmetric. Common form, elongated four-faced cubes {*hk*0}. Twinned on (111). Malleable; ductile. Fracture, hackly. H = 2½. G = 8·9. Copper-red. Lustre, metallic. Opaque. Fusible at 780° C. Soluble in nitric acid.

With the above description compare crystallised groups from **Lake Superior.**

Well-formed crystals of all the minerals belonging to this group are rare; and crystals of silver and copper resemble crystallised gold in being generally curved, uneven, or skeletal with rounded edges. Very fair cubes and

cubo-octahedra of silver have been found at Kongsberg in Norway ; the skeletal crystals of this metal are due to elongation or to parallel grouping in the direction of the cube-diagonals, as shown diagrammatically in Fig. 489. Similarly, copper is found in large and distinct cubes, octahedra, and dodecahedra in the Lake Superior mining region ; and the prevalence of faces $\{hk0\}$ in combination with these forms together with frequent elongation along the di-trigonal axis gives the crystals the aspect of com-

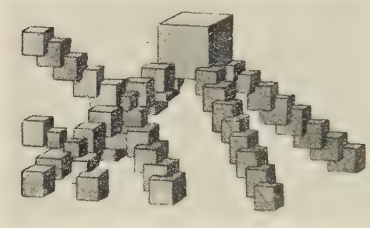


Fig. 489.—Silver. Skeletal Growth.

Fig. 490.—Copper from Lake Superior ; Twin Group.

plicated hexagonal forms. Fig. 490 (after Dana) represents cubes from Lake Superior elongated along the twin-plane (which is perpendicular to the paper), so that the crystal resembles a rhombic pyramid. These distortions, and also the twinning on (111), are as common with silver and

Fig. 491.—Wiry Silver from Norway (British Museum).

copper as with gold, and much that was said above about the latter will apply equally to them. Owing to these causes they frequently occur in dendritic and arborescent groups, of which the fronds are sometimes due to parallel growth of crystals so aggregated that the rays meet at angles of 60°, but more usually to twinning on faces of the octahedron (*cf.* Fig. 449,

p. 308). Silver is often found in remarkable filiform and stringy masses (Fig. 491), gold in thin sheets, scales, and flakes, or even as dust.

Noteworthy Localities for Silver and Copper :

Silver and copper are usually found in metalliferous veins ; the following two localities are remarkable and contribute typical specimens to most collections :

Kongsberg (Norway).—Silver, not only in wiry and stringy masses, but also in very distinct crystals of cubic habit in calcite, with quartz, blende, and galena ; the silver is often associated with argentite. It occurs in veins which are only productive of the metal and of silver ores where they intersect the so-called "fahlbands," which are grey belts of crystalline rock impregnated with metallic sulphides.

Lake Superior Mining Region.—Both copper and silver are here found under quite peculiar conditions. They occur together in basaltic rocks (melaphyres) which are accompanied by conglomerates and sandstones, in veins in the melaphyre and also in the amygdaloidal cavities of this rock ; they are associated with quartz, calcite, prehnite, laumontite, analcite, datolite, natrolite, fluor, and other minerals. Sometimes the amygdaloidal cavities are almost entirely filled with copper, and a single nodule of metal may consist partly of silver and partly of copper. The crystals of calcite sometimes enclose copper. The twin groups of copper are often elongated along the twin plane, as shown in Fig. 490.

Cobalt District (Ontario).—Very rich deposits of silver occur in veins in a conglomerate, along with bismuth, smaltite, niccolite, breithauptite, chloanthite, and other arsenides and sulphides of cobalt, nickel, and silver.

Other heavy metals occurring in the native state are platinum, palladium, iridium, iron, mercury, amalgam, and lead, of which all except platinum are very rare.

Platinum.—Pt. System, cubic, holosymmetric. Malleable ; ductile. Fracture, hackly. H = 4½ ; G = 19. Light steel-grey. Lustre, metallic. Opaque. Infusible. Insoluble in acids except *aqua regia*.

With the above description compare crystallised grains from **Nizhni Tagil** (Perm, Russia).

Platinum occurs almost exclusively in the form of nuggets and grains in river-gravels ; it has probably been derived from peridotites or serpentine-rocks, in which it has occasionally been found *in situ*. It usually contains palladium and iridium, which belong to the same isomorphous group, and iron.

Mercury (Germ. *Quecksilber*) is only found in liquid globules ; but crystals of mercury obtained by freezing at −40° C. have been shown by X-ray analysis to have a rhombohedral structure.

Native **amalgam**, an alloy of silver and mercury, is found at Moschel (Rhenish Bavaria) in bright silver-white crystals {100}, {110}, {111}, belonging to the cubic system. It is probably a compound, though its composition is uncertain.

Iron occurs as a principal constituent of many meteorites, and has been found in basic igneous rocks at Disco Island in West Greenland. It invariably contains nickel.

It was formerly supposed that all native iron was meteoric, but the Disco iron has been proved to be of terrestrial origin, for it is associated with a basalt containing iron disseminated in small nodules which are evidently constituents of the rock.

The native metals are seldom pure, and isomorphous mixtures or alloys are common. Gold, as we have seen, always contains silver, the quantity varying from 0·1 to 30 or more per cent; silver may contain both gold and copper; copper occasionally contains silver. Platinum contains iron, iridium, and palladium.

Their malleability, colour, hardness, and density are sufficient to distinguish the native metals from all other minerals; *e.g.* gold from iron-pyrites or chalcopyrite, and gold dust from mica scales; silver from argentite and other sectile sulphides; platinum from cobaltite; copper from niccolite.

Platinum and gold are not liable to tarnish; silver is usually more or less blackened by superficial alteration and sometimes converted into the black sulphide of silver (argentite); copper is generally brown or black on a tarnished surface, and is very liable to alteration, passing into the blue carbonate (chessylite), the green carbonate (malachite), or the red oxide (cuprite), by all of which it is often encrusted.

Several of these metals have been found in very large masses; the "Welcome" gold nugget found at Ballarat in Australia weighed 184 lbs.; a mass of silver, 5 feet long, from Cobalt in Ontario, now preserved at Toronto, weighs 1640 lbs.; and a mass of copper found in the Lake Superior mines was 45 feet in length and weighed 420 tons. Iron has also been found in large masses weighing as much as 20 tons at Disco Island; the Cranbourne meteoric iron (from Australia) in the British Museum weighs $3\frac{1}{2}$ tons, and still larger masses of meteoric iron have been found at several places in South America, where the dryness of the climate has preserved them from rusting. The meteoric iron found at Cape York in North Greenland in 1897 was estimated to weigh about 100 tons.

SECTION II

THE HALOIDS

FLUOR

Fluor.—Fluoride of calcium ; CaF_2 ; Ca = 51·3, F = 48·7.
Cubic, holosymmetric. Common form, cube.

$$A = \{100\},\ h = \{310\},\ t = \{421\}.$$

Interpenetrant twins ; twin axis [111] (the cube diagonal). Cleavage {111}, perfect. Brittle. Fracture, sub-conchoidal. H = 4 ; G = 3·2. Purple. Streak, white. Lustre, vitreous. Transparent. Refraction very weak ; $\mu = 1{\cdot}43$. Dispersion weak. Fusible with difficulty. Decomposed by sulphuric acid.
With the above description compare crystals from **Weardale** (Durham).

Fluor, or fluor-spar (Germ. *Flussspath*, Fr. *chaux fluatée, fluorine*), is the only common mineral which contains the element fluorine in any large proportion. It was in this mineral that Scheele discovered fluorine in 1771, although glass had been etched by means of fluor-spar and sulphuric acid about a century earlier.

Fluor is found very widely distributed and in beautiful crystals. It was known in the early history of mining as a frequent associate of metallic minerals under the name *marmor metallicum* and was much valued as a flux ; the name is derived from *fluo*, I flow.

The habit of fluor is remarkably constant ; no mineral crystallises more persistently in cubes ; other forms occasionally make their appearance, but the habit of the combinations is almost always the same. The cube sometimes has its edges bevelled by a four-faced cube {*hk*0}, generally {310} (Fig. 492) ; more rarely truncated by the dodecahedron, as in some specimens from Redruth in Cornwall.

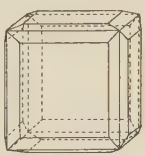


Fig. 492.—Fluor. Combination {100}, {310}.

The octahedron occurs occasionally as a simple form ; the well-known "rose-fluors," the pink crystals from Göschenen and Chamonix, are octahedra, as are also colourless crystals from Kongsberg in Norway and from Striegau in Silesia, and also the pink fluor found in the Island of Giglio near Elba. The edges of the octahedron are rarely truncated.

The low four-faced cube {310} occurs as a simple form ; {*hk*0} is so rare in other minerals that it is sometimes known as the "fluoroid."

This form is especially characteristic of certain violet-coloured crystals from Trevaunance Mine, St. Agnes, Cornwall, where it is combined with the cube. Other simple forms are rare; the dodecahedron and the three-faced octahedron {441} have both been recorded from Striegau in Silesia. The six-faced octahedron $t\{421\}$ occurs only in combination, and replaces the corners of the cube (Fig. 493) in the large yellowish crystals from Menheniot in Cornwall.

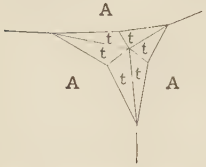


Fig. 493.—Fluor. Cube-corner with t {421}.

The above instances illustrate the great variety of forms found in any mineral which has been closely studied, even though the common specimens (as in fluor) may be quite simple.

The structure of fluor has already been described (see p. 293).

Fluor can be etched with hydrochloric acid, or with sodium carbonate; both solvents appear to give holosymmetric etched figures; the acid produces square hillocks and the alkali square pits on the cube-faces.

Twins are exceedingly common; two cubes are united by interpenetration according to the law: twin-axis, the cube-diagonal (*i.e.* a line parallel to a dodecahedron-edge), the corners of one cube projecting through the faces of the other. In these twins, at the exact point where an edge emerges, the cube-face is often raised into a very low pyramid consisting of four vicinal faces $\{hk0\}$, as mentioned on p. 109. They are faintly visible in Fig. 494. The indices of these vicinal faces are very high, *e.g.* {32.1.0}.

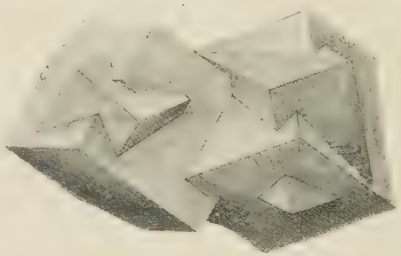


Fig. 494.—Fluor. Group of Twinned Cubes.

The faces of fluor are usually smooth and bright, with the exception of the octahedron, which is dull. Drusy and polysynthetic crystals are common. The druisiness of the octahedron and some other faces is often due to a polysynthetic growth of small cubes; an octahedron may consist of cubes large enough to be visible, as shown in Fig. 446; such polysynthetic growth need not interfere with the brightness of the *cube*-faces, since these are composed of faces of the sub-individuals which all fall into the same plane.

Fluor presents a great variety of colour; colourless crystals are rare; yellow, blue, green, and violet shades are common, and the rose fluors from Göschenen have been mentioned above. Amethystine and green fluors from the North of England and yellow from Saxony are common in museums. The colour is changed by heat and is supposed to be due to hydrocarbons, which may also account for a loss of weight experienced by the coloured crystals when heated. The cubes are sometimes banded with layers of different colours parallel to the cube-faces.

Most fluor exhibits a weak birefringence, which also varies in bands when the crystal is viewed between crossed nicols, indicating lamellation

parallel to the cube-faces; a section parallel to (100) shows a square banding, one parallel to (111) shows a triangular banding.

No relation has been traced between the colour and composition of the mineral, and there is no evidence that the birefringent lamellæ are due to the alternation of isomorphous compounds or to zones of varying composition. Colourless (Swiss) crystals are free from birefringence.

"Fluorescence" derives its name from this mineral, and is best shown by some of the richly coloured Cumberland specimens which appear amethystine or plum-blue by reflected and pale green by transmitted light.

The green and red crystals are strongly phosphorescent when heated; the name "chlorophane" was given to certain fluors which phosphoresce in green colours, in the belief that they were a new mineral.

Owing to its low refractive power and slight dispersion, combined with the absence of birefringence, fluor is very valuable for optical purposes and is used in making "apochromatic" microscope objectives; but suitable colourless isotropic crystals are extremely rare.

Being almost the only substance which is not attacked by free fluorine, fluor-spar was used by Moissan for vessels and stoppers in his experiments on the isolation of fluorine. The presence of free fluorine has been established in a very dark violet fluor-spar from Quincié, Dept. du Rhône.

Fluor is readily distinguished from all other common minerals possessing a vitreous lustre by its very perfect octahedral cleavage.

Two unusual varieties of this mineral are—massive fluor, a compact substance without cleavage and having a splintery fracture; and earthy fluor, which is quite soft and lustreless.

The beautiful substance worked in Derbyshire as an ornamental material for vases, etc., under the name "Blue John," is a crystalline fluor which occurs lining metalliferous veins and consists of bands of varicoloured crystals.

Fluor is chiefly found as a vein-mineral associated with metallic ores, with barytes, calcite, etc.; it is also especially characteristic of those tin-bearing veins which are distinguished by the presence of the fluoriferous compounds, tourmaline, lepidolite, topaz, apatite, etc., and are supposed to be due to pneumatolysis or the action of vapours of tin fluoride (see p. 414).

No minerals are isomorphous with fluor except perhaps **hydrophilite**, $CaCl_2$, which has been found as a sublimation product at Vesuvius, and which crystallises in small cubes.

Some Noteworthy Localities:

Weardale (Durham) and **Alston** (Cumberland). — Beautiful plum-coloured or green cubes, very frequently twinned by interpenetration, come from veins in the limestone, and the associated minerals may be quartz, calcite, pyrites, blende, galena, barytes, and chalybite. The calcite is generally in flat rhombohedra $\{110\}$ with the prism $\{2\bar{1}\bar{1}\}$, and the chalybite or brown spar is also in similar flat rhombohedra. The barytes is in the white platy curved masses generally known as "cawk."

The fluor is sometimes spangled over with glassy crystals of quartz, or with crystals of calcite or chalybite.

Derbyshire.—From the lead mines come purple and lilac cubes, sometimes with a yellow centre, on vein-quartz or crystallised calcite, associated with cubo-octahedra of galena and black blende; the calcite in prisms terminated by {110} or in the flat rhombohedra alone.

St. Agnes (Cornwall).—From the metalliferous veins in the slate (or "killas") in this tin-mining district, deep violet four-faced cubes {310}, generally combined with small faces of the cube, upon dark crystallised chlorite with quartz and cubes of pyrites. The fluor is sometimes green below, and passes into deep violet on the surface.

Chamonix (Savoy).—Beautiful rose-red *octahedra* on smoky quartz with titanite and adularia.

Gersdorf (Saxony).—Transparent brown and yellow cubes are associated with groups of tabular barytes and small chalcopyrite crystals of tetrahedral habit.

The only haloids, in addition to fluor, which are at all common or important are some of the minerals belonging to the salt group, and the mineral cryolite.

THE SALT GROUP

Salt.—Chloride of sodium; NaCl; Na = 39·4, Cl = 60·6.

Cubic; symmetry, tesseral holoaxial. Common form, cube. Cleavage {100}, perfect. Brittle. Fracture, conchoidal. H = $2\frac{1}{2}$; G = 2·14. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; $\mu = 1{\cdot}54$. Taste, saline. Fusible. Soluble in water.

With the above description compare crystals from **Wieliczka** (Poland).

Sylvite.—Chloride of potassium; KCl; K = 52·4, Cl = 47·6.

Cubic; symmetry, tesseral holoaxial. Common form, cube. Cleavage {100}, perfect. Brittle. Fracture, uneven. H = 2; G = 1·98. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; $\mu = 1{\cdot}49$. Taste, saline, bitter. Fusible. Soluble in water.

With the above description compare crystals from **Stassfurt** (Prussia).

Rock-salt crystallises in cubes, generally without any modifications; good examples have come from Stassfurt in Prussia and from Wieliczka in Poland; octahedral crystals occur but are comparatively rare.

The natural crystals differ considerably in appearance from those which are obtained by the evaporation of brine in the salt-manufacture of Cheshire and other places; the latter are almost always skeletal cubes or "hopper-shaped" crystals formed of a number of small elongated cubes built up to form a hollow pyramid.

Sylvite (so called from *sal digestivus Sylvii*, the old pharmaceutical name for the salt) was first discovered as a volcanic sublimation at Vesuvius, but far finer specimens have been subsequently found associated with the salt deposits of Stassfurt and of Kalusz in Galicia; among these are crystals as perfect as those of salt and very much richer in faces.

Crystals of both these minerals have forms which appear to be holosymmetric ; but etched figures on cube-faces consist of square pits whose edges are slightly inclined to those of the cube (*cf.* Fig. XXIX, p. 93) and indicate that the symmetry is really holoaxial. Octahedra of sylvite, when etched with water, develop faces of {931} arranged in accordance with holoaxial symmetry.

In both minerals twinning is almost unknown ; but twin-lamellæ have been noticed in salt.

Ordinary massive, fibrous, or granular salt is mostly impure, containing magnesium chloride and sulphates of calcium and magnesium ; and it may assume various tints of yellow, red, and blue ; very remarkable is a deep blue variety from Stassfurt, to be seen in most collections, of which the colour has been ascribed variously to a lower chloride of sodium, to colloidal sodium, to sulphur, to organic materials, and to an interference effect due to included cavities. It is true that salt may be coloured blue by heating in sodium vapour, but there is no direct evidence that the blue colour of the rock-salt is due to a lower chloride, or to sodium, and its cause is still unknown.

Both salt and sylvite are readily soluble in about three parts of water ; the violet colour which sylvite should give to flame may be masked by the presence of sodium ; but the two minerals may be easily recognised by their characteristic tastes combined with the perfect cubic cleavage. Both salt and sylvite frequently show traces of birefringence, caused by strain.

Both minerals are highly diathermanous, and cleavage-blocks of rock-salt have for this reason been valuable in thermal experiments where it has been necessary to enclose gases, for instance, in a tube with transparent ends which transmit the heat-rays with facility.

Rock-salt and sylvite were among the first minerals whose crystalline structure was ascertained by means of X-rays ; and it was from them that the proof was obtained that crystals of this kind are built up of interpenetrant lattices each composed of atoms of one kind—in this case Na (or K) and Cl—rather than of a single lattice composed of molecules NaCl, as explained on p. 287, where the structure in question is shown in Fig. 427. These structures are holosymmetric ; the holoaxial symmetry shown by the crystals may possibly be due to a want of symmetry in one or both kinds of the component atoms, Na (K), or Cl.

To the same group belong the following :—

Sal-ammoniac, NH_4Cl, has been found in white dodecahedral crystals as an incrustation upon lava at Mount Vesuvius and other volcanoes. Artificial crystals sometimes show faces of {875} indicating holoaxial symmetry.

Cerargyrite ("horn silver," chlorargyrite), AgCl, like the bromide and iodide of silver, has a very characteristic horny appearance, often referred to by the authors of the sixteenth century, who describe a mineral which is transparent like the horn of a lantern. Crystals are rare, but cubes bearing faces of {110}, {111}, etc., are found, and are sometimes twinned on the octahedron face.

The haloids of silver are readily recognised by their adamantine lustre, horny appearance, and sectility; they readily fuse and yield a globule of metallic silver. Silver chloride is the compound precipitated by hydrochloric acid in solutions of silver salts; this may serve to remind the student that cerargyrite is insoluble in acids, but soluble in ammonia.

Like the silver compounds used in photography, this mineral is rapidly altered by exposure to light, turning to a dark colour; in Nature it is found of many colours, grey, brown, green, yellowish, and bluish.

The chlorine in all the minerals of this group may be detected by the deep blue colour imparted to the oxidising flame when they are heated in a microcosmic bead saturated with oxide of copper.

The salt group includes also **bromargyrite** (AgBr) and isomorphous mixtures of the chloride with bromide (**embolite**) and with bromide and iodide of silver (**iodembolite**), as well as the chloride and iodide of copper, which all occur as minerals and belong to the cubic system.

X-ray analysis has shown, however, that the structure is not the same throughout the group; for while sylvite, cerargyrite, and bromargyrite have the same structure as salt, and are isomorphous with it, the copper haloids have that of blende (Fig. 429, p. 290). Sal-ammoniac appears to be dimorphous, having the salt structure above 183° C., while at the ordinary temperature its Cl-atoms appear to form a simple cubic lattice, each cell of which has a N-atom at its centre. The position of the H-atoms is unknown. Thus both modifications belong to the cubic system, and have identical angles, but they differ in their structure.

Silver iodide, which occurs as the mineral **iodyrite**, crystallises in the hexagonal system, with di-hexagonal polar symmetry. It is, however, dimorphous and passes into a cubic modification when heated to 146° C.

CRYOLITE

Cryolite.—Fluoride of sodium and aluminium; Na_3AlF_6; Na = 32·9, Al = 12·8, F = 54·3.

Monoclinic.

$$a : b : c = 0{\cdot}9662 : 1 : 1{\cdot}3883. \quad \beta = 89° 49'.$$

$m = \{110\}$, C = {001}, $r = \{011\}$, $v = \{101\}$, $k = \{\bar{1}01\}$, A = {100}, $p = \{111\}$.

mm (110) : ($1\bar{1}0$) = 88° 2′, Cm (001) : (110) = 89° 52′, Ck (001) : ($\bar{1}01$) = 55° 17′.

Cleavage (or parting ?) {001} perfect, {110}, and {$\bar{1}01$}. Brittle. Fracture, uneven. H = $2\frac{1}{2}$; G = 3·0. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; β = 1·36. Birefringence weak, positive. Axial plane and obtuse bisectrix perpendicular to (010); acute bisectrix inclined at 44° 5′ to normal of (001), and at 11° 12′ to normal of ($\bar{1}01$); 2E = 59° 24′; $\rho < v$. Easily fusible. Decomposed by sulphuric acid.

With the above description compare crystallised material from **Arksukfiord** (Greenland).

Cryolite is an important material in the manufacture of aluminium by electrolysis, the electrolyte used being alumina dissolved in a fused mixture of cryolite and fluor. There is a large bed of massive cryolite in gneiss at Ivigtut in Arksukfiord (West Greenland), where it was discovered about 1795. It is a colourless or pure white substance, but is in parts coloured red or brown by ferric oxides. The surfaces of the cracks in the massive mineral are lined with clear transparent crystals, which resemble cubes with a pronounced cubic cleavage, and these are generally disposed in parallel positions. The mineral is easily proved to be a fluoride by the

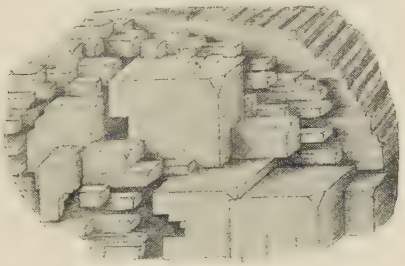


Fig. 495.—Cryolite.

evolution of HF when it is heated with sulphuric acid, and is distinguished from fluor by the nearly rectangular cleavage, the oblique striation (Fig. 495), and by the ready fusibility. Cryolite melts in the flame of a candle, and received its name (κρύος, λίθος, frost-stone) from this characteristic.

Cryolite is pseudo-cubic : its crystalline system is difficult to determine, and for a long time it was doubtful whether the mineral was monoclinic or anorthic. Recent examination of good crystals has shown it to be monoclinic, with complex twin-lamellation to which the parting, resembling cleavage, is due.

Cryolite is dimorphous, and changes into a cubic modification at 570° C.

SECTION III

THE MONOSULPHIDES

THE GALENA GROUP

Galena.—Sulphide of lead; PbS; Pb = 86·6, S = 13·4.

Cubic, holosymmetric. Common form, cubo-octahedron.

$$A = \{100\},\ o = \{111\},\ d = \{110\},\ p = \{221\}.$$

Cleavage {100}, perfect. Almost sectile. Fracture, even. H = 2½; G = 7·5. Lead-grey. Streak, lead-grey. Lustre, metallic. Opaque. Easily fusible, after decrepitation. Decomposed by nitric acid.

With the above description compare crystals from **Neudorf** (Harz).

Galena (Germ. *Bleiglanz*) is the common ore of lead, and argentiferous galena is of even greater value and importance as a profitable ore of silver. The name galena is used by Pliny. The mineral is a frequent constituent of metalliferous veins, where it sometimes occurs as fine crystals, usually cubes or cubo-octahedra (Figs. 496 and 500), and generally of cubic habit. At some localities, as at Neudorf in the Harz, the habit is octahedral, and the octahedron-edges are bevelled by a series of planes $\{hhl\}$ which give the crystal quite a rounded appearance (Fig. 497).

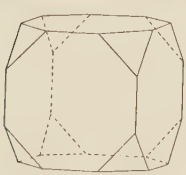


Fig. 496.—Galena. Cubo-octahedron.

The cube-faces of galena often consist in reality of very flat vicinal faces, not only $\{hk0\}$ as in fluor, but also $\{hkk\}$; the latter replace each cube-face by four (nearly) square facets which almost fall into a plane. The faces of galena are rarely smooth or brilliant.

Twinning is not common, but sometimes takes place on the spinel type, the axis of twinning being a di-trigonal axis, and the plane of composition the octahedron-face to which this axis is perpendicular; sometimes the individuals interpenetrate, as in Fig. 498; and in either case they are flattened along the plane of composition, so that the twin may present the appearance of one thin hexagonal plate lying upon another.

Crystals of galena are sometimes traversed by striæ and bands whose direction is shown in Fig. 499; these can be seen as nicked lines upon the cleavage-surfaces and are supposed to be twin-lamellæ parallel, usually, to planes of {441}, but also to other planes, such as (331) (113). Such lamellæ sometimes give quite a streaky appearance to massive galena;

they are perhaps due to pressure, since gliding along these planes can be artificially produced by squeezing a crystal of the mineral.

The perfect cubic cleavage of galena is its most conspicuous feature. A very remarkable, though rare, variety which has now been found at several different localities possesses, not cubic, but perfect *octahedral* cleavage; this curious exception has not been satisfactorily explained; the crystals exhibiting octahedral cleavage have in most cases been found to contain from 1 to 2 per cent of Bi_2S_3; the cleavage is said to become cubic after the mineral has been heated, and the change takes place without decrepitation, which is all the more remarkable, (1) because ordinary galena decrepitates when heated, and (2) sudden changes in crystalline structure are not infrequently accompanied by decrepitation; it is also remarkable that no change in density is produced by the heating.

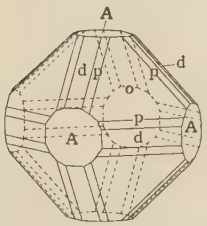


Fig. 497.—Galena, from Neudorf; *o* {111}, A {100}, *d* {110}, *p* {221}.

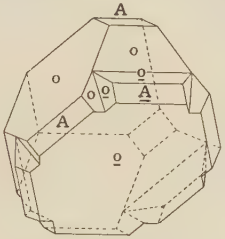


Fig. 498.—Galena, twinned on (11$\bar{1}$).

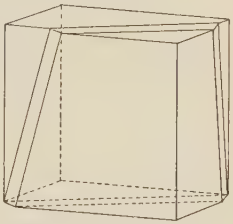


Fig. 499.—Galena with Twin-Lamella (44$\bar{1}$).

In galena the lead atoms and the sulphur atoms are arranged in the same way as are the sodium and chlorine atoms in rock-salt (p. 288).

Galena is usually found granular and massive, sometimes almost compact (Germ. *Bleischweif*), but in almost all specimens the brilliant facets of the cubic cleavage are to be distinguished on a fractured surface and give the mineral a shining appearance. Experiments on the etching and the percussion-figures of galena all confirm its apparently holosymmetric character.

Galena is easily recognised by the cubic cleavage, and the identification is confirmed by the softness, lead-grey colour, high density, and reduction on charcoal to a globule of lead. The cleavage is shown on the left-hand side of Fig. 500. Almost all galena contains silver, and although this does not often amount to more than one per cent, the mineral is one of the most profitable ores of silver.

A very remarkable occurrence is that at Commern in the Eifel, where galena is found in the Bunter sandstone as concretionary nodules of spherical shape.

Galena is sometimes tarnished blue; when decomposed, it generally gives rise to carbonate and sulphate, so that it is often accompanied by colourless crystals (as at Monte Poni, in Sardinia), or white earthy crusts, of cerussite and anglesite.

In the lead mines of Huelgoat in Brittany, and in Wheal Hope, near Truro, in Cornwall, were formerly found large hexagonal prisms consisting of galena ; these are crystals of lead phosphate which have been converted into sulphide, in other words, *pseudomorphs* of galena after pyromorphite.

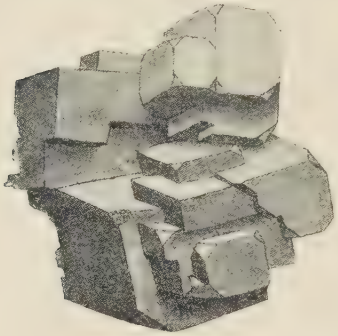


Fig. 500.—Galena, from Joplin, Missouri.

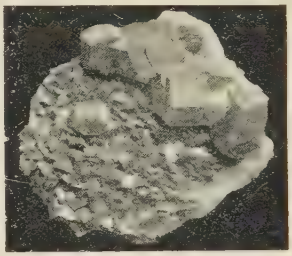


Fig. 501.—Galena on Chalybite, from Neudorf (British Museum).

Some Noteworthy Localities :

Derbyshire (and the North of England).—Crystals of cubic habit, generally cubo-octahedra, associated with calcite, fluor, quartz, blende, pyrites, and barytes, in veins traversing limestone. These veins are, and have long been, worked as lead mines.

Neudorf (and other localities) in the Harz district.—Crystals of cubo-octahedral habit (Fig. 501) and " spinel twins," associated with quartz, calcite, chalybite (in smooth brown rhombohedra {100}), fluor, chalcopyrite, and blende, also bournonite and tetrahedrite, in veins traversing clay-slates ; the galena is argentiferous.

Jasper County (Missouri).—At the Joplin mines, fine cubes, with octahedron-faces, upon a white or pink crystallised dolomite ; with ruby-coloured blende, and chalcopyrite in small crystals of tetrahedral habit which are usually situated on the blende.

Argentite.—Sulphide of silver ; Ag_2S ; Ag = 87·1, S = 12·9.

Cubic. Common form, cube. Cleavage {100} {110}, imperfect. Sectile. Fracture, sub-conchoidal. H = 2½ ; G = 7·3. Dark lead-grey. Streak, the same, shining. Lustre, metallic. Opaque. Fuses readily and yields sulphurous fumes.

With the above description compare crystals from **Kongsberg** (Norway).

Argentite, the only important cubic monosulphide in addition to galena and blende, sometimes occurs in rude, uneven cubes or octahedra, but is more usually platy, earthy, dendritic, etc. ; it is generally converted on the surface, like many other silver ores, into an earthy black sulphide of silver. It is an important ore of silver and sometimes sufficiently abundant to be largely worked as such, *e.g.* in Nevada and in Mexico. The mineral is easily recognised by its sectility and shining streak, and by the bead of silver yielded by reduction on charcoal ; it might be confused only with

rare sulphides and selenides of silver, mercury, and copper, of which several exist ; but it does not itself contain either selenium, mercury, or copper.

THE BLENDE GROUP

Blende.—Sulphide of zinc ; ZnS ; Zn = 67·1, S = 32·9.

Cubic. Symmetry, di-tesseral polar. Common form, {110} with tetrahedron. Twinned by rotation in the plane (11$\bar{1}$), with twin axis [11$\bar{1}$] (cube-diagonal).

$d = \{110\}$, $m = \{311\}$, A = {100}, $o = \{111\}$, $\omega = \{1\bar{1}1\}$.

Cleavage {110}, perfect. Brittle. Fracture, conchoidal. H = 3½ ; G = 4. Yellow. Streak, pale yellow. Lustre, adamantine. Sub-transparent. Refraction very high ; $\mu = 2{\cdot}37$. Fusible with difficulty. Decomposed by hydrochloric acid.

With the above description compare crystals from **Kapnik** (Hungary).

Blende, the most important ore of zinc, is an extremely common mineral, especially as a constituent of metalliferous veins. The name, a German

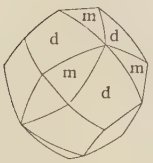


Fig. 502.—Blende, *d* {110} with *m* {311}.

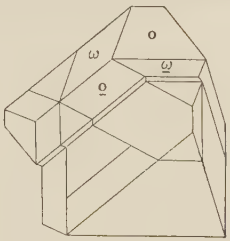


Fig. 503.—Blende, Spinel Twin on [11$\bar{1}$].

Fig. 504.—Blende, twinned on [11$\bar{1}$].

mining term signifying " blind " or " deceptive," was originally given to this substance as a metallic ore which resembled galena but yielded no lead; its other modern name, sphalerite, is a translation of blende (*σφαλερός*, deceptive). Although no longer likely to be mistaken for galena if attention be paid to the cleavage, blende is so variable in colour and appearance that it often deceives the eye and is difficult to recognise.

The common black crystals are combinations of the dodecahedron {110} with rounded faces of {311} (Fig. 502). These frequently show small brilliant triangular faces of the tetrahedron {1$\bar{1}$1} on those corners of the dodecahedron from which {311} is absent. The green and yellow crystals from Hungary display faces of the dodecahedron, tetrahedron, cube, and other forms. Simple tetrahedral crystals are rare ; black tetrahedra were formerly found in some of the mines in the St. Agnes district in Cornwall ; they sometimes have their edges truncated by the cube, and their corners by the complementary tetrahedron. Whenever the two tetrahedra occur together one is smooth and bright, while the other is striated or dull. These two forms may also be distinguished by etching with hydrochloric acid (Fig. 505). The polar character of the tesseral axes is apparent also in the structure of the crystals (p. 290, *cf.* Fig. 508).

At most localities the crystals of blende are traversed by twin lamellæ parallel to the tetrahedron faces. Sometimes simple twin-crystals of the spinel type, of octahedral habit, are found; in these the bright faces of the tetrahedron o {111} on one individual are opposite to the dull faces of the other tetrahedron ω {1$\bar{1}$1} (Fig. 503), so that the twinning is to be described as due to hemitropy about the di-trigonal axis, and not to reflection over the tetrahedron-face to which that axis is perpendicular. Even in a "spinel" twin of this sort each individual is often traversed by twin-lamellæ parallel to the other tetrahedron-faces. In a twinned dodecahedron the six faces of one individual which are parallel to the twin-axis coincide with six faces of the other individual (Fig. 504), so that the twinning may at first sight be overlooked; but supplementary twinning such as would confer a holosymmetrical aspect on the crystals, as in diamond, is not found in blende.

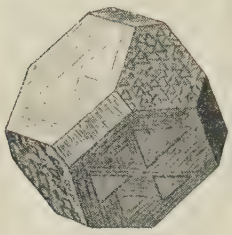


Fig. 505.—Blende {111}, {1$\bar{1}$1}, {100}, etched.

In addition to etching, pyroelectric experiments have proved the polar nature of the trigonal axes of blende; if an insulated plate cut perpendicular to one of these axes be brought into contact with a small heated metal hemisphere it becomes positively or negatively electrified at the point of contact, according as the one face or the other is experimented on; the electrification is observed by means of an electrometer connected with the heated metal.

The perfect dodecahedral cleavage (angles of 60°) and adamantine lustre serve to distinguish blende from the minerals which it resembles; the black varieties may at first glance be mistaken for hornblende, which has nearly the same cleavage-angle, but only two cleavage-directions.

Blende is very commonly found massive, botryoidal, and curvilaminar; the curvilaminar and reniform varieties are known in Germany as *Schalenblende* and *Leberblende* respectively. Most of the *fibrous* varieties of zinc sulphide, on the other hand, may be recognised under the microscope as birefringent, and are in reality the hexagonal zinc sulphide, wurtzite (see p. 370). Blende itself is usually quite isotropic.

Most specimens contain iron, to which the great variety of colour is probably due; the black blende contains a considerable proportion; this appears to be an isomorphous intermixture of FeS, which may be present to the extent of 15 or 20 per cent. Indium and gallium were both discovered in blende, and the mineral may also contain manganese, cadmium, thallium, and tin. Absolutely pure blende, free from iron, such as that from Franklin (New Jersey), known as "cleiophane," is colourless.

The mineral is remarkably free from alteration or tarnish, but is sometimes converted into white earthy sulphate or carbonate.

The zinc in blende is detected by the sublimate on charcoal in the reducing flame, but the mineral may also yield a coating of cadmium oxide; sulphur is found by heating in the open tube; iron will generally be indicated by the borax bead after roasting.

Blende is a very common occupant of metalliferous veins, especially in association with galena, chalcopyrite, and other sulphides, with barytes, with fluor, and with quartz.

Some Noteworthy Localities :

Alston Moor, and other places in the lead mining districts in the north of England.—Black lustrous blende (known locally as " black jack ") occurs in veins and cavities (" flats ") of the mountain limestone, associated with quartz, calcite, galena, pyrites, fluor, and barytes ; the blende is in curved crystals of the habit of Fig. 502. Especially fine are the groups which are accompanied by rounded or crested aggregations of white platy barytes (locally known as " cawk ").

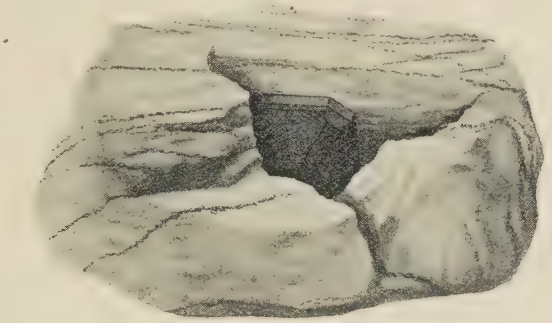


Fig. 506.—Blende, in Dolomite, from Binnenthal.

Binnenthal (Switzerland).—Small cracks in the snow-white granular dolomite contain brilliant brown tetrahedra of blende accompanied by equally brilliant crystals of galena, scarlet realgar, and other metallic sulphur compounds. The blende is sometimes in crystals of cubo-octahedral habit, showing frequent twin-lamellæ. The dolomite is traversed by thin bands of crystallised iron-pyrites, as shown in Fig. 506.

Schemnitz and other localities in the gold and silver mining districts of Hungary.—Metalliferous lodes in propylite and other rocks contain pale yellow and greenish blende in complex crystals of dodecahedral habit, much laminated, and associated with quartz (often amethyst) of trigonal habit (Fig. 562, p. 424), argentiferous galena, pyrites, and chalcopyrite. See also the description of tetrahedrite from **Kapnik** (p. 393).

THE MILLERITE GROUP

Millerite.—Sulphide of nickel ; NiS ; Ni = 64·7, S = 35·3. Hexagonal.

$$a : c = 1 : 0{\cdot}988.$$

Brittle. H = 3½ ; G = 5·5. Brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. Easily fusible. Decomposed by nitric acid.

With the above description compare acicular crystals from **Merthyr Tydvil** (Glamorganshire).

Niccolite.—Arsenide of nickel ; NiAs ; Ni = 43·9, As = 56·1. Hexagonal.

$$a : c = 1 : 0{\cdot}819.$$

Brittle. Fracture, uneven. H = 5½; G 7·5. Copper-red. Streak, brownish-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystallised material from **Sangerhausen** (Prussian Saxony).

Millerite, capillary pyrites (Germ. *Nickelkies, Haarkies*), and **Niccolite,** nickeline, copper-nickel (Germ. *Rothnickelkies, Kupfernickel*), are two minerals which are easily recognised, millerite by its brassy colour, and by the fibrous or acicular structure (which is very unusual among the other yellow metallic sulphides). The finest acicular crystals, like hairs, occur in cavities of the clay ironstone at Merthyr Tydvil; fibrous velvety masses are worked at the Gap Mine in Lancaster County, Pennsylvania. The mineral yields the reaction for nickel in the borax bead; but it generally contains also copper, iron, and cobalt, which may partially mask this reaction.

Niccolite is recognisable by its remarkable reddish-bronzy colour, which is quite unlike that of any other mineral except breithauptite and the copper arsenides; the presence of arsenic and nickel is easily proved, and the mineral may also contain Sb, S, Fe, Co; and as the proportion of antimony increases it gradually passes into breithauptite.

The minerals belonging to this hexagonal group are remarkably different in their characters. Millerite only occurs in acicular or capillary crystals of extreme thinness seldom terminated, or in fibrous aggregates; niccolite is rarely crystallised, and then in imperfect hexagonal pyramids, of which only the terminations are developed. The corresponding antimony compound, **breithauptite,** NiSb, occurs massive or as little prisms of a peculiar purplish-bronzy colour.

To the same group belong the following:

Greenockite, CdS, which is a rare mineral found as little yellow hemimorphic pyramidal crystals (Fig. 507) dispersed on prehnite from the Glasgow and Greenock tunnel near **Bishopton** in Renfrewshire. ($a : c = 1 : 0{\cdot}811$.)

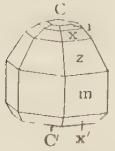


Fig. 507.—Greenockite; C {0001}, *i* {10$\bar{1}$2}, *x* {10$\bar{1}$1}, *z* {20$\bar{2}$1}, *m* {10$\bar{1}$0}, *x'* {10$\bar{1}\bar{1}$}, C' {000$\bar{1}$}.

Wurtzite, the "fibrous zinc blende," ZnS, resembles blende, but may be recognised by its birefringence. Crystals are extremely rare, but black terminated prisms having the form of greenockite (Fig. 507) have been found at Oruro in Bolivia, and their angles are near those of greenockite. ($a : c = 1 : 0{\cdot}817$.)

X-ray analysis has shown that greenockite and wurtzite have a structure which is very closely related to that of blende. In wurtzite, as in blende, every atom of zinc is at the centre of a tetrahedron formed of sulphur atoms, and *vice versa*. In the planes perpendicular to *one* of the trigonal axes of the tetrahedron, which forms the principal axis of the wurtzite crystal, the atoms are arranged as in blende, but the successive pairs of planes of this set are differently related to one another, each successive pair being rotated 180° about this axis from its position in blende (*i.e.* as if into

twin-position), with reference to the preceding pair. The resulting structure is shown in Fig. 508, which shows also for comparison the blende structure set up in the corresponding position.

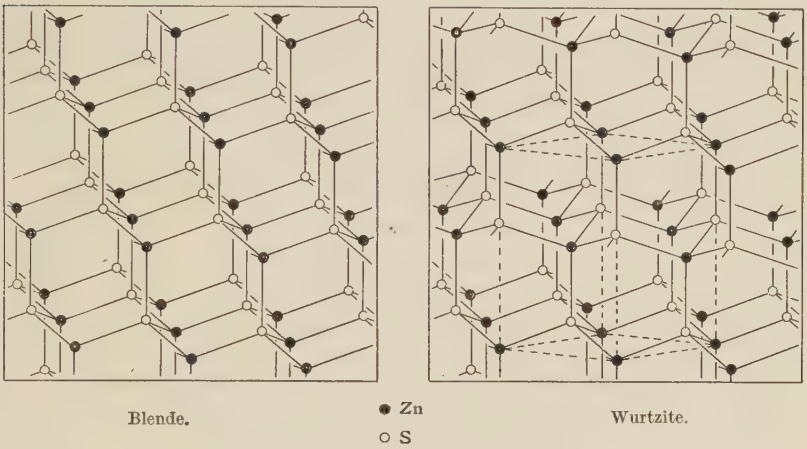


Fig. 508.—Structure of Blende and Wurtzite.

Pyrrhotite.—Sulphide of iron; FeS(?); Fe = 63·5, S = 36·5.

Hexagonal (or pseudo-hexagonal ?). Common form, hexagonal plates. Cleavage, hexagonal prismatic, $\{11\bar{2}0\}$, imperfect. Brittle. Fracture, uneven. H = 4; G = 4·6. Bronze-yellow. Streak, greyish-black. Lustre, metallic. Opaque. Magnetic. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Kongsberg** (Norway).

Pyrrhotite, magnetic pyrites (Germ. *Magnetkies, Leberkies*). This mineral is of somewhat doubtful composition, and almost always contains more sulphur than would correspond to the simple formula FeS. The analyses indicate considerable variation, and different formulæ, ranging from Fe_6S_7 to $Fe_{11}S_{12}$, have been assigned to pyrrhotite. But some of the purest specimens approach very closely to the monosulphide, FeS, in composition. The excess of sulphur may be due to the presence of admixed pyrites or more probably to loosely combined sulphur.

In the absence of optical measurements it is impossible to say for certain whether pyrrhotite is hexagonal or pseudo-hexagonal (orthorhombic). If hexagonal, it would appear to belong to this group; one of its pyramid angles is 53° 11′, while one of those of greenockite is 52° 20′. The etching figures on the basal plane, the prism-cleavages, the curve of thermal conductivity, and the magnetic properties all point to hexagonal symmetry, though there is no evidence of a polarity of the vertical axis. On the other hand, thermo-electric properties appear to suggest that pyrrhotite is only pseudo-hexagonal.

Pyrrhotite is usually massive with a tendency to laminar structure; but large crystals, thick hexagonal plates more than an inch in diameter,

from Morrho Velho in Brazil, are preserved in the British Museum. Good but small crystals have been found at Kongsberg in Norway, and at Andreasberg in the Harz.

The peculiar bronzy colour of pyrrhotite (*πυρρός*, reddish), inclining to pinchbeck-brown, combined with its magnetic character, serve to distinguish it from iron- or copper-pyrites, and from other sulphides which may resemble it when they are slightly tarnished.

THE COPPER-GLANCE GROUP

Copper-glance.—Sulphide of copper; Cu_2S; Cu = 79·9, S = 20·1. Orthorhombic.

$$a : b : c = 0{\cdot}582 : 1 : 0{\cdot}970.$$

C = {001}, *e* = {023}, *z* = {113}.

$$Ce(001) : (023) = 32° 53', \quad Cz(001) : (113) = 32° 44'.$$

Twinned on (110), on (032), and on (112). Cleavage {110}, imperfect. Sectile. Fracture, conchoidal. H = 2½; G = 5·7. Lead-grey. Streak, black. Lustre, metallic. Opaque. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Redruth** (Cornwall).

Copper-Glance, redruthite, chalcocite, vitreous copper (Germ. *Kupferglanz*), is a good example of an orthorhombic mineral with pseudo-hexagonal symmetry, the prism angle being near 60°; like aragonite and chrysoberyl, it still further simulates the symmetry of the hexagonal system by twinning about the prism-planes; and it exhibits a great variety both of form and twinning.

Characteristic among Cornish varieties are flat-topped prisms from Redruth, thin plates and stout drusy prisms from St. Ives, and interpenetrating twins consisting of two tabular crystals twinned on (032) and intersecting at an angle of 69°, from St. Just.

The pseudo-hexagonal twins and triplets resemble those of chrysoberyl, and are distinguished by striæ on the basal plane parallel to B (010), (*cf.* Fig. 581, p. 442). Very similar specimens are found at Bristol, Connecticut.

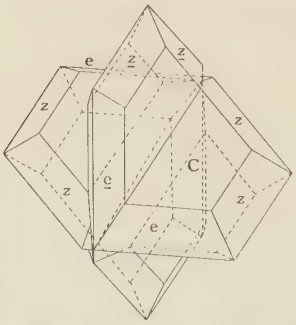


Fig. 509.—Copper-glance, C {001}, *e* {023}, *z* {113}; twinned on (112).

The intersecting twins have either (112) for twin plane, when they cross at angles of 87° 54′ (Fig. 509), or are twinned on (032), when the angle $C\underline{C}$ is 69°; the form (032) is not found as a face on any of the crystals. Copper-glance occurs largely both massive and compact, and is of a dark grey metallic colour, with sometimes a rather greasy lustre. On exposure it blackens (owing to surface-alteration into melaconite (?)); it is also liable to tarnish, and becomes converted into covellite, the blue sulphide, or into erubescite (see p. 390). Being somewhat sectile it might be confused with argentite, and the form of the crystals makes it somewhat

resemble stephanite, but the bead of copper, instead of silver, obtained by reduction on charcoal, serves to distinguish it from those minerals. It sometimes contains a little iron.

A mineral known as **acanthite,** which has been found in the silver mines of Freiberg in Saxony, possesses all the chemical characters of the cubic mineral argentite, which belongs to the galena group, but occurs in long blade-shaped crystals. This has been referred to the orthorhombic system and supposed to be isomorphous with copper-glance. It is possible, however, that these crystals are merely misshapen crystals of argentite.

Under **stromeyerite** are classed certain silver ores which may be called argentiferous copper-glance: *i.e.* isomorphous mixtures of copper-glance and acanthite; but as these ores are rarely crystallised, it is difficult to refer them to this group with certainty, although orthorhombic crystals having such a composition are certainly known.

CINNABAR

Cinnabar.—Sulphide of mercury; HgS; Hg = 86·2, S = 13·8.

Hexagonal; symmetry, trigonal holoaxial (quartz class). Common form, rhombohedron with basal pinakoid. Cleavage, the prism $\{2\bar{1}\bar{1}\}$, good. Sectile. Fracture, uneven. H = 2½; G = 8·2. Cochineal-red. Streak, vermilion. Lustre, metallic-adamantine. Subtransparent. Refraction very strong; $\omega = 2{\cdot}85$. Birefringence positive, very strong; $\epsilon - \omega = 0{\cdot}35$. Rotatory polarisation very strong. Volatile. Decomposed by nitric acid.

With the above description compare crystals from **Almaden** (Spain).

Cinnabar (Germ. *Zinnober*) is remarkable for its enormous refractive power, and strong birefringence, but still more for the remarkable rotatory polarisation, which, as in quartz, is associated with trigonal holoaxial symmetry; the rotatory power of cinnabar is no less than fifteen times that of an equal thickness of quartz; the plane of polarisation of red light is rotated through about 325° by a plate 1 mm. thick. Faces $\{hkl\}$ which display the true symmetry are rare; the form $\{621\}$ has been observed. The crystals are often twinned on the basal plane (111), and then show Airy's spirals when viewed in the direction of the principal axis in convergent light.

The mineral is more often found massive or earthy, and then has a rich vermilion colour; much of the ore from Idria in Carniola is mixed with impurities and is brown and slaty. Cinnabar may always be recognised by its true vermilion streak, which is sufficient to distinguish it from cuprite, realgar, and proustite, though the latter mineral resembles it somewhat both in colour, lustre, and streak. The deposition of mercury on heating either in the open tube alone, or in the closed tube with sodium carbonate, affords confirmatory evidence.

A black mercury sulphide which has been found in tetrahedral crystals in California is known as **metacinnabarite.**

Covellite, CuS, a blue microcrystalline mineral, derived from the alteration of copper-glance, may perhaps be allied to cinnabar.

SURVEY OF THE MONOSULPHIDES

The monosulphides (arsenides, etc.) form an interesting family, falling into groups of minerals crystallising in three different systems, of which the principal members are the following :

Cubic.	Hexagonal.	Orthorhombic.
	I.	
Blende ZnS	Wurtzite ZnS	
	Greenockite CdS	
Alabandite MnS		
(Artificial FeS)	Pyrrhotite FeS	
Pentlandite (Fe, Ni)S	Millerite NiS	
	Niccolite NiAs	
	Breithauptite NiSb	
	II.	
Galena PbS		
Argentite Ag_2S		Acanthite Ag_2S ?
Jalpaite $(Ag, Cu)_2S$		Stromeyerite $(Cu, Ag)_2S$
(Artificial Cu_2S)		Copper-glance Cu_2S
	III.	
Metacinnabarite HgS	Cinnabar HgS	
	Covellite CuS	

Of these the orthorhombic minerals are all pseudo-hexagonal, so that the connection is even more close than at first sight appears.

FeS in the cubic form has been prepared artificially (though the form usually obtained is hexagonal), and also enters into the composition of blende. It also occurs together with NiS in a mineral, **pentlandite** (Fe, Ni)S, which, though not well crystallised, has an octahedral cleavage. The compound FeS is found as a brassy substance (troilite) in some meteorites. X-ray analysis shows that this has a hexagonal structure, and it is probably identical with pyrrhotite.

Both selenides and tellurides of lead and silver are found as cubic minerals and belong to the same group with galena ; Ag_2S is proved to be dimorphous by its occurrence as an isomorphous mixture with Cu_2S in stromeyerite, even if the mineral known as acanthite be not really isomorphous with copper-glance. Cu_2S is obtained in octahedra as a fusion-product in copper-furnaces, and a mineral with cubic cleavage from Mexico, known as **jalpaite,** is a mixture, $(Ag, Cu)_2S$, corresponding to stromeyerite.

Among these minerals blende and alabandite are undoubtedly di-tesseral polar (tetrahedral), but galena and argentite apparently holosymmetric ; cinnabar is trigonal holoaxial (quartz class) and differs in dimensions

and symmetry from greenockite, which is di-hexagonal polar; wurtzite is occasionally found well crystallised in the zinc-furnaces, and the crystals are di-hexagonal polar and completely isomorphous with greenockite.

The monosulphides therefore fall naturally into three isodimorphous series, the first comprising the zinc group, the second the lead group, and the third the mercury sulphides.

SECTION IV

THE DISULPHIDES

THE PYRITES GROUP

Pyrites.—Sulphide of iron; FeS_2; Fe = 46·5, S = 53·5.

Cubic; symmetry, tesseral central. Common forms, cube, octahedron, pyritohedron {210}.

A = {100}, *o* = {111}, *d* = {110}, *e* = {210}, *t* = {421}, *s* = {321}.

Supplementary twins. Brittle. Fracture, conchoidal. H = 6; G = 5·1. Pale brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. On charcoal, burns, and gives off sulphurous fumes. Fuses to magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from the **Island of Elba.**

Pyrites (Germ. *Eisenkies*, or *Schwefelkies*, Fr. *fer sulfuré*) is one of the commonest and most ubiquitous of minerals; as small crystals and

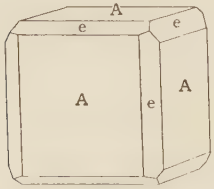


Fig. 510.—Pyrites, A {100}, *e* {210}.

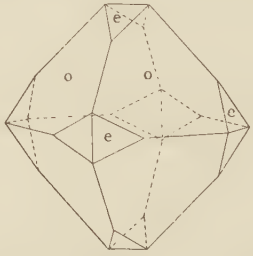


Fig. 511.—Pyrites, *o* {111}, *e* {210}.

specks of a brassy-yellow colour it may be noticed in all manner of rocks from basalts to slates; as lustrous cubes and cubic combinations it is very frequent in metalliferous veins. By the ancients it was not distinguished from chalcopyrite, and the name pyrites as used by Dioscorides and Pliny (first century A.D.) includes several minerals, which (as implied by the name) yield sparks when struck with the hammer; perhaps not only sulphides, in which the sparks are due to the combustion of the mineral itself, but also hard minerals, like flint or emery, in which the sparks are due to the combustion of the metal of the hammer.

Pyrites is the best-known and most typical example of tesseral central

symmetry in the cubic system. It commonly occurs in simple cubes, but even these generally betray their true symmetry by the well-marked striations (Fig. 86, p. 46), which are parallel to alternate pairs of edges; the striations on each face being therefore at right angles to those upon the adjacent faces; these are due to an oscillatory combination of the cube with {210} (see p. 306). Other simple forms are: the octahedron, whose faces are generally smooth and bright; and the pentagonal dodecahedron {210}, which is so characteristic of this mineral that it is often called the "pyritohedron"; the dodecahedron, on the other hand, is conspicuous by its rarity. Numbers of forms occur in combination. Among the combinations the form {421}, Fig. 513, is easily recognised because its edges are truncated by {210}; {321} replaces the edges between {111} and {210} (Fig. 516); and {210} is generally present. The octahedron may often be recognised as a small bright triangular face truncating the corner of {210} (Fig. 516) and is sometimes laminar in structure. The two supplementary pyritohedra,

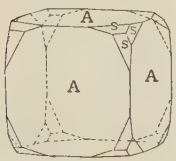


Fig. 512.—Pyrites, A {100}, *s* {421}.

Fig. 513.—Pyrites, *s* {421}.

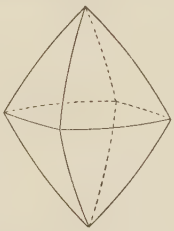


Fig. 514.—Pyrites, misshapen, from French Creek.

{210} and {120}, which would make up a four-faced cube (Fig. 27), are rarely, if ever, found together. There is nothing in the shape to distinguish the pyritohedron {210} from the supplementary pyritohedron {120}. But X-ray analysis shows that the structure and spacing of the two sets of planes is quite different.

Very remarkable are the crystals from French Creek Mines in Pennsylvania, which have the aspect of simple *tetragonal bipyramids* (Fig. 514); these are explained as due to the development of eight faces belonging to the three-faced octahedron {332}; some of the crystals even resemble orthorhombic bipyramids. Another example of misshapen pyrites is afforded by thin rod-like crystals from Lobenstein, in Thuringia; these are elongated cubes. Twinning is rare, but brown pyritohedra found in marl at Minden in Prussia are beautiful examples of supplementary twinning (Germ. "*Zwillinge des eisernen Kreuzes*"), one crystal penetrating entirely through the other (Fig. 515); they may be described as twinned by reflection over any face of {110}, or by hemitropy about any edge of {111}.

It has been noticed that some pyritohedra have their faces striated parallel to the cube-edges (Fig. 516), and others (more rare) perpendicular thereto. Now it has also been proved that if a crystal of the former kind be placed in contact with the two ends of a copper wire and one of the junctions be warmed, an electric current will pass along the wire from the

hot junction to the colder one, *i.e.* the pyrites is thermo-electrically positive to copper; whereas the crystals of the latter kind are thermo-electrically negative, the current passing in the opposite direction. The difference is very great, one sort of crystal being more positive in this respect than antimony, and the other sort more negative than bismuth; some pyrites crystals consist in part of positive and in part of negative material.

It is possible, as in diamond, that apparently simple crystals are really supplementary twins, and that the true symmetry of pyrites is that of the ullmannite class, tesseral polar. This suggestion is confirmed by the *tetrahedral* habit of some artificial crystals of pyrites. It is true that the figures produced by etching with *aqua regia* are symmetrical about the cube-planes, but, as in diamond, this might possibly be the case with a completely interpenetrant supplementary twin.

Iron-pyrites is generally recognisable by its appearance; it is distinguished from chalcopyrite by the paler colour, the superior hardness,

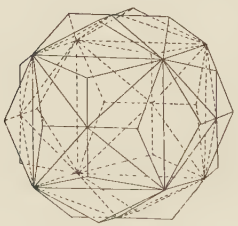


Fig. 515.—Pyrites, {210}, supplementary twin.

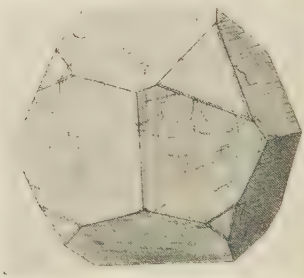


Fig. 516.—Pyrites, {210}, {111}, {321}, from Elba.

and the streak; pyrrhotite, the only other common mineral with which it might be confused, is always of a pinchbeck-bronze colour and is slightly magnetic. Some varieties of pyrites seem to be more liable to decomposition than others; this is probably due to their containing marcasite, which has the composition of pyrites but is a far less stable compound; the fibrous and stalactitic forms in particular become converted into iron sulphates and liberate sulphuric acid; some of these consist largely of marcasite. Ordinary pyrites is often converted into limonite and appears quite dark on the surface: this is the case, for example, with the twin crystals from Minden.

Pyrites sometimes contains nickel, cobalt, or copper; the first two, doubtless, as isomorphous intermixtures of the corresponding sulphides, the latter probably as chalcopyrite; silver and thallium are also sometimes present. But the most important impurity is gold, which often occurs disseminated minutely through crystallised pyrites and in sufficient quantity to render the mineral one of the chief sources of gold, just as argentiferous galena is one of the chief sources of silver. In pyrites, however, the gold is not present as an isomorphous compound, but as the metal.

A large quantity of gold is extracted from auriferous pyrites in various parts of the world: in the Rossland district of British Columbia, for instance, auriferous pyrites and chalcopyrite are largely worked. Much of the free gold in nature may have been originally derived from pyrites.

The chief commercial use of pyrites is for the manufacture of sulphuric acid and sulphur, and the ferric oxide obtained as a by-product in this process is used as rouge and polishing powder; some of the varieties which contain much admixed chalcopyrite are also worked as copper ores. The alum shales so largely used in the manufacture of alum are merely shales which are richly impregnated with pyrites and marcasite.

Pyrites often occurs massive or in nodular and stalactitic forms; the latter especially when it has resulted from the decomposition of organic materials. Fossils may consist of pyrites, and in such cases the mineral has doubtless been produced by reduction of solutions of ferrous sulphate through the action of the decaying organism. This may have been the origin of many nodules of pyrites and marcasite found in chalk and clay. The formation of sulphuric acid by the subsequent oxidation of the pyrites, and its action upon limestone, would account for the origin of the gypsum by which such fossils and nodules are often accompanied.

Some Noteworthy Localities:

Traversella (Piedmont).—Some of the finest specimens are from the iron mines of the Chiusella Valley, where the chief ore is a crystalline magnetite; and in druses of this mineral occur sometimes quite large isolated crystals and groups of pyrites. These are pyritohedra and combinations with cube, octahedron, and $\{hkl\}$, often associated with quartz and pearl-spar.

Island of Elba.—Equally perfect are the crystals from the iron mines of Rio, where they occur in connection with hæmatite deposits in a siliceous slate; the pyrites is very rich in faces and varied in habit (especially pyritohedral), often enclosing hæmatite, and sometimes altered to limonite.

Cornwall.—Generally in simple striated cubes with chalcopyrite or quartz in metalliferous veins traversing clay-slate, and often associated with chlorite.

Colorado.—Brilliant crystals, of varying habit and exceedingly rich in faces, come from the mines of Gilpin County.

The following minerals belong to the pyrites group and crystallise in the same forms and combinations.

Chloanthite.—Arsenide of nickel; $NiAs_2$; Ni = 28·1, As = 71·9.

Cubic; symmetry, tesseral central. Common form, cubo-octahedron. Cleavage {111}, imperfect. Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 6·5. Tin-white. Streak, greyish-black. Lustre, metallic. Opaque. Easily fusible. Soluble in nitric acid.

With the above description compare crystals from **Riechelsdorf** (Hesse).

Smaltite.—Arsenide of cobalt; $CoAs_2$; Co = 28·2, As = 71·8.

Cubic; symmetry, tesseral central. Common form, cubo-octahedron. Cleavage {111}, imperfect. Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 6·2. Tin-white,

slightly steel-coloured. Streak, grey-black. Lustre, metallic. Opaque. Easily fusible to a magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from **Schneeberg** (Saxony).

Cobaltite.—Arseno-sulphide of cobalt; CoAsS; Co = 35·5, As = 45·2, S = 19·3.

Cubic; symmetry, tesseral central (?). Common form, pyritohedron with cube. Cleavage {100}, fair. Brittle. Fracture, uneven. H = 5½; G = 6·2. Silver-white, slightly reddish. Streak, greyish-black. Lustre, metallic. Opaque. Fusible to magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from **Tunaberg** (Sweden).

The above three minerals closely resemble pyrites in their crystal characters. **Cobaltite** (Germ. *Kobaltglanz*) is found in very perfect octahedra, cubes, and pyritohedra, and their combinations, at Tunaberg in Sweden, in limestone in a gneiss, together with copper pyrites and other metallic ores. **Smaltite** (Germ. *Speiskobalt*) and **chloanthite** (Germ. *Weissnickelkies*) crystallise in imperfect cubes and cubo-octahedra, but are more usually massive, and sometimes, as in Saxony and Bohemia, reticulated. The thermo-electric characters of these minerals appear to be the same as those of pyrites. Smaltite and chloanthite graduate into each other by isomorphous intermixture, different specimens containing different proportions of cobalt and nickel; they usually contain also sulphur and iron. Smaltite and cobaltiferous chloanthite are the common ores of cobalt.

Ullmannite, NiSbS, is the nickel-antimony equivalent of cobaltite. This mineral occurs in Sardinia as cubes striated like pyrites, but in Carinthia as tetrahedra; it must therefore really belong to the tesseral polar class (p. 55).

In cobaltite the structure has been found to be similar to that of pyrites, one of each pair of sulphur atoms being replaced by an atom of arsenic, in accordance with the tesseral symmetry. In this structure there is no centre of symmetry as in pyrites, and it is therefore possible that cobaltite may really belong to the tesseral polar class, along with ullmannite.

All these minerals, owing to decomposition and oxidation, are liable to be accompanied by the corresponding sulphates and arsenates; these give a green colour to the nickel, and a pink colour to the cobalt compounds, by which they may often be recognised and distinguished.

THE MARCASITE GROUP

Marcasite.—Sulphide of iron; FeS_2; Fe = 46·5, S = 53·5.

Orthorhombic, holosymmetric.

$$a : b : c = 0{\cdot}766 : 1 : 1{\cdot}234.$$

$$m = \{110\},\ C = \{001\},\ l = \{011\},\ v = \{013\}.$$

$$mm\ (110) : (1\bar{1}0) = 74^\circ\ 55',\ Cl\ (001) : (011) = 50^\circ\ 59'.$$

Twinned on (110), less frequently on (101). Cleavage {110}, imperfect; {011}, very imperfect. Brittle. Fracture, uneven. H = 6; G = 4·8. Pale brass-yellow. Streak, greenish-grey. Lustre, metallic. Opaque. Reactions like those of pyrites. Decomposed by nitric acid.

With the above description compare crystallised groups from **Folkestone** (Kent).

Marcasite (Germ. *Strahlkies*) is not often found in simple crystals, but, owing to its multiple twinning, presents a great variety of shapes with jagged outlines and re-entrant angles, and has in consequence received many trivial names: such are "cockscomb-pyrites" (Germ. *Kammkies*), of which the specimens from Tavistock in Devonshire may be taken as an example, and 'spear-pyrites" (*Speerkies*), familiar as angular groups in the chalk of the south of England. These shapes are all due to twinning on (110).

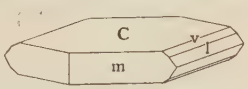


Fig. 517.—Marcasite, *m* {110}, C {001}, *l* {011}, *v* {013}.

Generally speaking, marcasite, as contrasted with pyrites, is much more apt to occur in fibrous, radiated, and concretionary forms, and comparatively seldom in distinct crystals. "Radiated pyrites" (*Strahlkies*) and "hepatic pyrites" (*Leberkies*) were names given to these varieties at a time when marcasite and pyrites were not distinguished as two minerals. The name marcasite is from an Arabic word used for crystallised pyrites of any sort during the Middle Ages.

Marcasite is very liable to decomposition; it is often converted on the surface into brown limonite; many specimens readily fall to pieces, especially when exposed to a moist atmosphere; the mineral becomes covered with efflorescent and fibrous growths of white ferrous sulphate, and the cabinets in which the mineral is kept contain free sulphuric acid.

In Nature marcasite occurs under much the same conditions as pyrites, but is not such a common mineral in the crystalline rocks and schists, or in metalliferous veins; it is more common than pyrites in the form of nodules and concretions of organic origin in sedimentary rocks.

A Noteworthy Locality:

Folkestone (Kent).—In chalk marl, here and at Dover, are found flat spear-headed groups (Fig. 518) locally supposed to be the heads of Roman weapons.

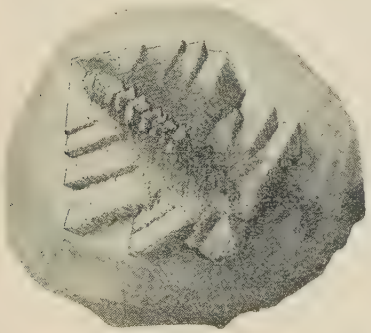


Fig. 518.—Marcasite in Chalk, from Dover.

These are twinned by repeated reflection across different faces of the prism {110}; as in aragonite (p. 105), repetition with inclined twin planes gives a stellate group of four or five crystals arranged about a centre, and so the form of Fig. 518. The striated faces which meet to form the ribs are the prisms {011} and {013}. The angle of the prism {110} is nearly one-fifth of 360°; this accounts for the frequency of a pentagonal grouping of marcasite as contrasted with the hexagonal grouping of aragonite.

Mispickel.—Arseno-sulphide of iron ; FeAsS ; Fe = 34·3, As = 46·0, S = 19·7. Orthorhombic, holosymmetric.

$$a : b : c = 0{\cdot}677 : 1 : 1{\cdot}188.$$

$$m = \{110\},\ e = \{014\},\ l = \{011\}.$$

$$mm\ (110) : (1\bar{1}0) = 68^\circ\ 13',\ ll\ (011) : (0\bar{1}1) = 99^\circ\ 50'.$$

Twinned on (101). Cleavage {110}, fair. Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 6·0. Silver-white. Streak, greyish-black. Lustre, metallic. Opaque. Fusible to a magnetic bead. Decomposed by nitric acid.

With the above description compare crystals from **Lostwithiel** (Cornwall).

Mispickel, arsenical pyrites or arsenopyrite (Germ. *Arsenkies*), is a fairly common mineral in various metalliferous veins, especially in those which yield tin, and it has been found well crystallised in several of the Cornish mines.

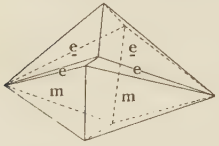


Fig. 519.—Mispickel, *m* {110}, *e* {014}, twinned on ($\bar{1}01$).

Like marcasite it is generally twinned, and some of the groups closely resemble those of marcasite. With the positions adopted above, both minerals twin according to two laws, namely, on (110) and on (101), but the former is the more common mode of twinning in marcasite and the latter in mispickel; mispickel affords, like aragonite, an instance of twinning upon a pseudo-hexagonal prism ; the angle of the prism {101} being 59° 22′ (Fig. 519). In marcasite the corresponding angle is 63° 40′. This large difference in the angles of the two minerals (and therefore in their axes) has raised some doubt as to whether they are to be regarded as isomorphous.

Some mispickel contains a considerable quantity (up to 9 per cent) of cobalt, due no doubt to isomorphous intermixture with the corresponding arseno-sulphide of cobalt, known as **glaucodote** ; this is of course easily detected in the borax bead.

Mispickel is a common ore of arsenic, and is largely worked as such in Cornwall. The name mispickel is an old German mining term of unknown derivation.

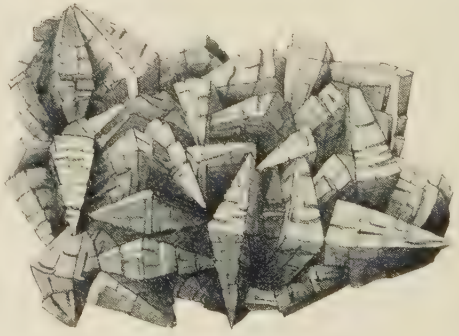


Fig. 520.—Mispickel from Tavistock (Devonshire) ; (British Museum).

The curious cruciform cavities filled with red earthy hydrate of iron found in slate at Clonmel in Ireland illustrate both the decomposition and the twinning of mispickel. They were called crucite or crucilite, and were supposed to be altered staurolite or some unknown mineral on account of their remarkable form,

crosses or stars with their arms meeting at angles of about 60° : there is no reason to suppose them anything else but mispickel prisms twinned on (101) which have been entirely decomposed.

SURVEY OF THE DISULPHIDES

The disulphides and arseno-sulphides constitute the following very complete and instructive isodimorphous series :

Cubic Series.		Orthorhombic Series.	
Pyrites Division.	Cobaltite Division.	Marcasite Division.	Mispickel Division.
Pyrites FeS_2		Marcasite FeS_2 Löllingite $FeAs_2$	Mispickel FeAsS
Smaltite $CoAs_2$	Cobaltite CoAsS	Safflorite $CoAs_2$	Glaucodote (Fe, Co)AsS
Chloanthite $NiAs_2$	Gersdorffite NiAsS Ullmannite NiSbS	Rammelsbergite $NiAs_2$	Wolfachite NiAsS
Hauerite MnS_2 Sperrylite $PtAs_2$			

So far as can be seen from the form of their crystals all the cubic members of the above series appear to be pyritohedral except ullmannite, which is tesseral polar. However, we have seen above that the structure of cobaltite appears to place this in the same class with ullmannite, and that there is some reason to think that pyrites may also possess this symmetry ; it is therefore possible that the whole cubic series may belong to the ullmannite class.

Hauerite is found in fine isolated octahedral crystals in clay at Kalinka in Hungary, and at Raddusa in Sicily. **Sperrylite,** the only natural compound of platinum, occurs as brilliant microscopic crystals (pyritohedral combinations) in a nickeliferous ore consisting of various sulphides at Sudbury in Ontario. Much larger brilliant crystals (up to nearly an inch in diameter) have quite recently been found in the Transvaal. Another member of the group is very rare, **laurite,** RuS_2, found in minute crystals in the platinum sands in Borneo.

The minerals grouped together under the name **gersdorffite** are mostly massive nickel ores containing a considerable quantity of iron and some cobalt.

It is remarkable that there is another arsenide of cobalt of quite different composition, $CoAs_3$, known as **skutterudite,** which is also cubic and pyritohedral.

SECTION V

THE SESQUI-SULPHIDES

THE STIBNITE GROUP

Stibnite.—Sulphide of antimony; Sb_2S_3; Sb = 71·7, S = 28·3.

Orthorhombic. Common form, prism {110} terminated by {111}.

$$a : b : c = 0{\cdot}993 : 1 : 1{\cdot}018.$$

$$m = \{110\},\ B = \{010\},\ p = \{111\}.$$

Bm (010) : (110) = 45° 13′, pm (111) : (110) = 34° 51′, Bp (010) : (111) = 54° 36′.

Cleavage {010}, perfect. Glide-plane, (001). Slightly pliable. Fracture, conchoidal. H = 2; G = 4·6. Steel-grey. Streak, lead-grey. Lustre, metallic. Opaque. Easily fusible (1). Volatilises. Decomposed by HCl.

With the above description compare crystals from **Felsöbanya** (Hungary).

Stibnite or antimonite (Germ. *Antimonglanz*) is the only important ore of antimony, and is found massive in considerable quantities; the best crystallised specimens are those from the antimony mines of Ichinokawa in the island of Shikoku, Japan, where it occurs, as at other localities, in long striated prisms, but of a great size (more than a foot in length) and extraordinarily rich in many brilliant pyramid faces. At other localities the crystals are terminated by p, and only a few other pyramids, such as {113}, {121}. The mineral can generally be recognised, even in massive specimens, by its perfect longitudinal cleavage and by horizontal lines and nicks on the cleavage surface which indicate a glide-plane parallel to the base {001}; owing to gliding along the plane of cleavage the crystals can be bent, and they are often found curved and warped. Very remarkable are the twisted crystals found in Japan, and in some other places (Fig. 521); there is no evidence that these can be explained by vicinal twinning like twisted quartz (p. 428), neither has stibnite a right- and left-handed character like quartz.

Fig. 521.—Stibnite, twisted crystal (Oxford Museum).

Stibnite is opaque to light except in very thin plates, which transmit the extreme red rays. It is, however, transparent to the ultra-red heat

rays, and for these it has been proved to be doubly refracting and to show extinction corresponding to its orthorhombic symmetry, a cleavage-plate being rotated between crossed nicols and the intensity of the transmitted rays being measured by a radiomicrometer.

The refractive indices for the red light transmitted by a very thin prism (line A) and also the double refraction are extraordinarily high :

$$\gamma = 4{\cdot}303,\ \beta = 4{\cdot}046,\ \alpha = 3{\cdot}194\ ;\ \gamma - \alpha = 1{\cdot}109.$$

The axial plane is (100) and the negative acute bisectrix perpendicular to (001).

A cleavage-surface of stibnite is excellently adapted to show that heat is unequally conducted in different directions in a crystal (see p. 121). The curve of conductivity is an ellipse, whose major axis coincides with the vertical axis *c* and the minor axis with the brachy-diagonal *a*. This is in accordance with the orthorhombic symmetry.

Massive specimens often have a fibrous structure ; the softness and fusibility of stibnite also serve to distinguish it from other sulphides containing antimony. It loses its brilliancy when exposed to the light and becomes black. The dark powder of stibnite was used in ancient times to darken the eyebrows, etc.

Stibnite is often accompanied by white and yellow oxides of antimony, resulting from its decomposition.

Some Noteworthy Localities :

Felsöbanya (Hungary).—Fine terminated crystals of stibnite occur in metalliferous quartz veins in trachyte, and are associated with barytes, blende, realgar, calcite, and quartz ; the stibnite sometimes penetrates the tabular crystals of barytes (Fig. 723, p. 589) ; it is partly coated with yellow crusts of blende or with chalcedony.

Japan.—From the antimony mines of the island of Shikoku have come the finest specimens of stibnite : large prisms terminated by numerous lustrous faces. A huge group in the British Museum is one of the most striking mineral specimens in that collection ; these crystals are sometimes as much as 18 inches long ; they are frequently bent at the end.

The stibnite group includes **bismuthite**, Bi_2S_3, a comparatively rare mineral, and one which is not found in terminated crystals. The striated prisms of bismuthite are usually acicular ; they possess the same cleavage as stibnite, and a similar prism-angle, but only one crystal from Bolivia has yielded a prism {101} from which the vertical axis can be calculated. Artificial crystals also present only the prism-zone.

The corresponding sulphide of arsenic, **orpiment** (Germ. *Auripigment, Operment*), is not often found crystallised ; small crystals can be extracted from clay at Tajowa in Hungary ; these possess the same cleavage and glide-planes as stibnite, but the angles differ considerably, so that there is some doubt whether orpiment is really isomorphous with stibnite and bismuthite.

As_2S_3	$a : b : c = 0{\cdot}603 : 1 : 0{\cdot}674$,	prism-angle 79° 20′.
Sb_2S_3	$a : b : c = 0{\cdot}993 : 1 : 1{\cdot}018$,	,, 89° 34′.
Bi_2S_3	$a : b : c = 0{\cdot}968 : 1 : 0{\cdot}985$,	,, 88° 8′.

Bismuthite is an opaque tin-white mineral of metallic lustre like stibnite; crystallised orpiment is a soft lemon-yellow translucent mineral of resinous lustre (pearly on the cleavage surface); the streak is bright yellow; the mineral is often found foliated or earthy as a decomposition product of realgar.

Realgar, AsS, is found in fine translucent red monoclinic crystals in metalliferous veins in Hungary and other places; also as beautiful little crystals with blende and pyrites in the dolomite of the Binnenthal (see p. 369). It very readily changes to yellow orpiment when exposed to the action of light.

SECTION VI

THE SULPHO-FERRITES

CHALCOPYRITE

Chalcopyrite.—Sulpho-ferrite of copper ; $CuFeS_2$; Cu = 34·7, Fe = 30·4, S = 34·9. Tetragonal ; symmetry, di-tetragonal alternating.

$$a : c = 1 : 0{\cdot}985.$$

$o = \{111\}$, $\omega = \{1\bar{1}1\}$, $e = \{101\}$, $C = \{001\}$, $z = \{201\}$, $d = \{114\}$, $d' = \{1\bar{1}4\}$, $u' = \{4\bar{4}1\}$.

$Ce\ (001) : (101) = 44° 34'$, $Co\ (001) : (111) = 54° 20'$, $o\omega\ (111) : (1\bar{1}1) = 70° 7'$.

Twinned by rotation in a plane of $o\ \{111\}$. Cleavage {201}, imperfect. Somewhat brittle. Fracture, conchoidal. H = 4 ; G = 4·2. Brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from the **Harz**.

Chalcopyrite, copper-pyrites, or towanite (Germ. *Kupferkies*, Fr. *cuivre jaune*), is one of the commonest ores of copper, and the mineral from which most of the copper of commerce is derived ; it is a common constituent of metalliferous veins, where it sometimes occurs in beautiful crystals, rivalling those of iron-pyrites in perfection and lustre.

The angles of this mineral are very nearly those of the cubic system, and its axes are consequently very nearly equal. The crystals are commonly bisphenoids which resemble regular tetrahedra, or sometimes octahedra which really consist of two such complementary tetrahedra ; the "octahedron"-angles are then 70° 7′ and 71° 20′ (instead of 70° 32′). The mineral was in fact supposed to be cubic until in 1822 this small difference was established by accurate measurements. The true symmetry can sometimes be made out by careful examination of certain crystals which appear at first sight to be combinations of tetrahedron and cube ; it will sometimes be found that of the six tetrahedron-edges only four are truncated, and this is sufficient to show that the truncating faces belong to a square prism (Fig. 123) and not to a cube. In other cases the basal pinakoid may be present without this square prism (Fig. 133). The edges of the octahedral crystals are truncated by the form $e\ \{101\}$, and the corners are often replaced by $z\ \{201\}$; the basal pinakoid is rare.

The habit of the crystals varies much according to the bisphenoids present, which may either be acute (Fig. 522) or obtuse (d in Fig. 523).

The structure of chalcopyrite is similar to that of blende (Fig. 429), with the necessary shortening of the vertical axis, the horizontal planes of zinc atoms being replaced alternately by planes of iron and of copper atoms.

The faces usually have a platy structure, and are much striated. The true symmetry of the mineral is clearly displayed by the striations and superficial characters of the "octahedron"-faces. The faces of one "tetrahedron" (o), which usually predominates, are dull, and are liable to oxidation, while those of the complementary "tetrahedron" (ω) are bright. These differences are especially important in the interpretation of the twins, which are generally of one or other of two kinds.

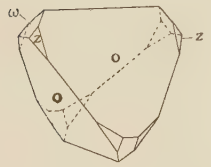


Fig. 522.—Chalcopyrite, o {111}, ω {1$\bar{1}$1}, z {201}.

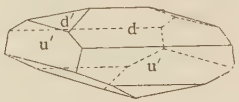


Fig. 523.—Chalcopyrite, d {114}, d' {1$\bar{1}$4}, u' {441}.

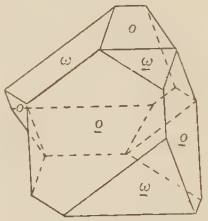


Fig. 524. — Chalcopyrite, o {111}, ω {1$\bar{1}$1}, twinned by rotation in (11$\bar{1}$).

(1) Twins by rotation in a plane of o {111}, with composition along this plane. These are twins of the spinel type (Fig. 524), in which, as in blende (see Fig. 503, p. 367), dull faces of o meet bright faces of ω at the twin-junction; they must therefore be described as due to hemitropy in the plane of a face o, and not to reflection over this plane (see p. 98).

Composite twins (Fig. 525), found at Neudorf in the Harz, consist of

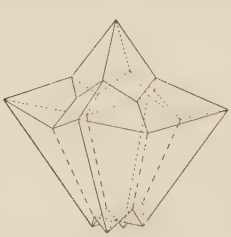


Fig. 525.[1] —Chalcopyrite, {201}, twinned on {111}.

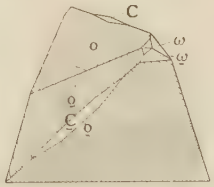


Fig. 526.[1] — Chalcopyrite, o {111}, ω {1$\bar{1}$1}, C {001}, twinned on (01$\bar{1}$).

five individuals, a central crystal to which four other crystals are symmetrically united by twinning on the four faces of the form {111}.

It will be noticed that the form z {201} is not a bisphenoid like o, but is a bipyramid.

(2) Reflection-twins, with twin-plane e (101), and composition along this plane. Here o is opposed to o, and ω to ω, across the twin-junction; the doublet is symmetrical to the composition-plane, and can only be described as due to reflection over that plane, and not to hemitropy.

Fig. 526 represents the crystal (from Cornwall) on which the nature of this twin-growth was first decisively established by Fletcher.

[1] The crystals of Figs. 525 and 526 have been rotated from the customary position; that of Fig. 525 through 45°, that of Fig. 526 through 90°, about the vertical axis.

Like other compounds of sulphur and iron, chalcopyrite is readily liable to tarnish and surface alteration. Beautifully iridescent tarnished masses, common in Cornwall and elsewhere, are known as "peacock-copper"; the prevalent blue colour of this tarnish may be due partly to the conversion of the chalcopyrite into covellite, CuS.

A curious massive variety is that found in some Cornish mines, and known as "blistered copper ore"; this is botryoidal or reniform, with a smooth, brassy surface.

Chalcopyrite is distinguished from iron-pyrites by its softness, being easily scratched by the knife; also by yielding on treatment with nitric acid a green solution, which becomes blue on addition of ammonia; it can scarcely be mistaken for the sectile gold.

The variations in the composition of chalcopyrite are probably to be explained by the mechanical intermixture of iron-pyrites. Thus two analyses of a single specimen from Freiberg gave the following:

	Cu	Fe	S	
I	25·78	35·16	37·52	corresponding nearly to $2CuFeS_2 + FeS_2$
II	30·66	34·11	35·23	„ „ $4CuFeS_2 + FeS_2$

At Joplin in Jasper County, Missouri, chalcopyrite occurs in "tetrahedra" disposed in parallel position upon blende; and the iridescent drusy crust which covers the tetrahedrite from Herodsfoot Mine, near Liskeard, consists of tarnished chalcopyrite.

Like iron-pyrites, chalcopyrite occurs in many and various surroundings, and is found massive in very large deposits often mixed with iron-pyrites, pyrrhotite, and also with nickel sulphides. In many places auriferous chalcopyrite is worked as an ore of gold.

Some Noteworthy Localities:

St. Agnes (Cornwall).—The mineral was called towanite, after the

Fig. 527.—Chalcopyrite with Quartz, from St. Agnes (British Museum).

Towan Mine at this locality, where it occurred in large crystals of scalenohedral habit in metalliferous veins associated with quartz, chalybite, blende, cassiterite, and chlorite (Fig. 527).

French Creek (Pennsylvania).—Very perfect isolated sphenoidal crystals have been found in chlorite at the French Creek iron mines; these are acute bisphenoids {332}, like Fig. 132, p. 59.

Of the other compounds of copper, iron, and sulphur which may with chalcopyrite be classed together under the name sulpho-ferrites, one only is sufficiently common to be mentioned here.

Erubescite.—Sulpho-ferrite of copper; Cu_3FeS_3; Cu = 55·7, Fe = 16·3, S = 28·0. Cubic. Common form, cube. Twinned by rotation on cube-diagonal; twin-axis [111]. Cleavage {111}, imperfect. Slightly sectile. Fracture, sub-conchoidal. H = 3; G = 5·0. Dark bronze. Lustre, metallic. Streak, greyish-black. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Carn Brea** (Cornwall).

Erubescite, bornite, variegated copper ore (Germ. *Buntkupfererz*, Fr. *cuivre panaché*), occurs in irregular interpenetrating cubes twinned by rotation about the cube-diagonal [111]; but more usually massive. Very characteristic is the peculiar dark bronzy colour of this mineral on a freshly fractured surface, and the vivid bluish tarnish which it quickly assumes on exposure (hence the miners' name, "horseflesh ore"). These superficial characters are sufficient to distinguish erubescite from argentite, and the sectility from other sulphides. The composition of the crystals is accurately represented by the formula given above, but massive specimens vary considerably, the percentage of copper ranging from 55 to 70; this may, however, be due to intermixture of copper-glance.

SECTION VII

THE SULPHANTIMONITES, ETC.

THE TETRAHEDRITE GROUP

Tetrahedrite. — Sulphantimonite of copper; Cu_3SbS_3; Cu = 46·7, Sb = 29·8, S = 23·5.

Cubic; symmetry, di-tesseral polar. Common form, tetrahedra.

$o = \{111\}$, $\omega = \{1\bar{1}1\}$, $d = \{110\}$, $n = \{211\}$.

Twin axis, a cube-diagonal. Brittle. Fracture, sub-conchoidal. H = 3½; G = 4·7. Steel-grey. Streak, dark brown. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Kapnik** (Hungary).

Tetrahedrite, fahl-ore, or grey copper (Germ. *Antimonfahlerz*, Fr. *cuivre gris*, *panabase*), is a common ore of copper, and was taken above (p. 47) as the representative of di-tesseral polar symmetry. The crystals are almost invariably of tetrahedral habit; the tetrahedra often have their edges bevelled by {211} (Fig. 528), and their corners replaced by the dodecahedron which constitutes a little three-faced pyramid upon each tetrahedron corner (Fig. 529). When the complementary tetrahedron

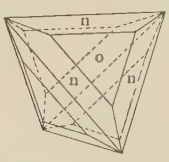


Fig. 528.—Tetrahedrite, *o* {111}, *n* {211}.

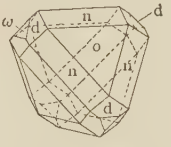


Fig. 529. — Tetrahedrite, *o* {111}, *n* {211}, *d* {110}, *ω* {1$\bar{1}$1}.

ω {1$\bar{1}$1} occurs, its faces are usually dull (specimens from Kapnik), or pitted with triangular markings (specimens from Dillenburg), and so may be distinguished from the tetrahedron *o* {111}. Where only one tetrahedron is present, it is apparently the latter. Sadebeck attempted to distinguish them by means of the other forms by which they are accompanied. He established the fact that when both the complementary forms {211} and {2$\bar{1}$1} occur on the same crystal, the former is striated perpendicular to the dodecahedron-edge which it truncates, while the latter is striated parallel

to the dodecahedron-edge which it truncates. Hence these forms serve to determine the tetrahedron which they accompany. Tetrahedrite is sometimes twinned on a cube-diagonal [111] as twin-axis, one crystal having the edges and corners of smaller individuals projecting from its faces; the positions of the latter are obtained by hemitropy about an axis, such as [11$\bar{1}$], Fig. 530, joining a corner of the tetrahedron to the centre of the opposite face, *i.e.* about a cube-diagonal. It is noteworthy that supplementary twinning, in which two individuals interpenetrate with their edges at right angles to each other (*cf.* Fig. 478, p. 340), is rare in tetrahedrite.

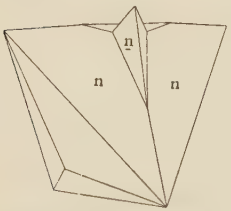


Fig. 530.—Tetrahedrite, $n\{211\}$, twinned about axis [11$\bar{1}$].

Tetrahedrite is never pure, but always contains other elements in isomorphous mixture, such as As, replacing Sb, and Ag, Hg, Fe, Zn, replacing Cu, and its appearance and characters vary considerably with its composition. We shall therefore consider this mineral and those which are isomorphous with it, together, as one group; the two chief members being:

Tetrahedrite, Cu_3SbS_3
Tennantite, Cu_3AsS_3

The old German mining term "Fahlerz" included both the sulphantimonite, tetrahedrite, and the corresponding sulpharsenite, tennantite (Germ. *Arsenfahlerz*), with their isomorphous mixtures. Tennantite rarely contains other metals than copper and iron, but tetrahedrite and those fahl-ores which contain both antimony and arsenic vary widely in composition, owing to the partial replacement of the copper in the above formula by iron, silver, zinc, or mercury; in both minerals, but especially in tennantite, bismuth may partially replace the antimony and arsenic respectively. Many analyses may be reduced to the type $3R'_2S \cdot X_2S_3$ where $R' = Cu, Ag, Hg$, and $X = Sb, As, Bi$, but they indicate also a small proportion of iron and zinc, probably present as the compound $6R''S \cdot X_2S_3$.

The following analyses illustrate the great range of variation in the composition of fahlerz:

	S	Sb	As	Cu	Fe	Zn	Ag	Hg
Cornwall	23·95	23·97	...	44·08	2·17	3·64	1·31	...
Clausthal	24·10	26·80	...	35·70	4·50	0·90	8·90	...
Kapnik	25·31	24·21	2·88	37·83	0·94	7·25	1·32	...
Schwatz	22·96	21·35	...	34·57	2·24	1·34	...	15·57
Cornwall	26·61	...	19·03	51·62	1·95	...	...	...

The last of these is nearly pure tennantite. "Freibergite" (Germ. *Weissgültigerz*) is a name applied to the argentiferous varieties; that from Freiberg may contain as much as 30 per cent of silver. The fahlerz from Schwatz in the Tyrol, which contains 16 per cent of mercury, is sometimes called "schwatzite." Freibergite is lighter in colour than tetrahedrite; its streak is often reddish; schwatzite occurs in black drusy

crystals characterised by a *dodecahedral* habit (resembling Fig. 531), the predominant faces being those of the dodecahedron, while the tetrahedron-faces are quite small.

Tennantite itself differs from tetrahedrite in being usually dodecahedral or cubic in habit (Fig. 531); it is also darker in colour.

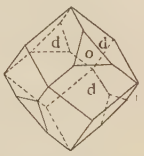


Fig. 531.—Tennantite, *d* {110}, *o* {111}.

The varieties of tennantite which contain zinc have been distinguished by the names *Kupferblende* and "sandbergerite," and show a tendency to develop large faces of {211}, so that some crystals resemble Fig. 107, p. 52.

Fahlerz which contains lead has a slightly resinous lustre, but, whatever their differences in appearance, all the minerals and mixtures belonging to this group are recognisable, if crystallised, by their polar symmetry, metallic lustre, and absence of cleavage, combined with the reactions for copper, together with either antimony or arsenic.

Some Noteworthy Localities:

Binnenthal (Switzerland).—The most beautiful examples of tennantite, though small, are the brilliant crystals very rich in faces, which occur with other metallic minerals in the white dolomite of the Binnenthal, described on p. 369 under blende. These were formerly supposed to be a distinct mineral and were known as "binnite."

Herodsfoot Mine (Liskeard, Cornwall).—The tetrahedrite formerly found here is a vein-mineral on quartz veinstone, and occurs in large bevelled tetrahedra (Fig. 528), completely coated with brassy, or brilliantly tarnished, drusy chalcopyrite; on these specimens, crystals of quartz are often grouped into rectangular tables, possibly pseudomorphous after barytes, and the specimens may bear also galena and bournonite.

The minute crystals of copper-pyrites which form a drusy coating on the Liskeard tetrahedrite are arranged in parallel positions, so that the principal axis of each crystal coincides in direction with one of the cubic axes of the tetrahedrite; they have probably resulted from the decomposition of the latter.

Kapnik (Hungary).—Sharply crystallised simple tetrahedra, and tetrahedra with edges bevelled by {211}, upon crystallised quartz of trigonal habit with brown blende and chalcopyrite; the vein-stuff often contains pink rhodonite; a white clay usually occupies some of the corners between the quartz crystals.

Redruth (Cornwall).—Tennantite in dark grey dodecahedra, with cube- and tetrahedron-faces; the crystals are small and are associated with arsenic.

A table of the better established metallic compounds of sulphur with arsenic, antimony, and bismuth will be found on p. 604; they are for the most part rare; in addition to fahlerz, the only members of the class which are to be found in almost all collections are stephanite, pyrargyrite and proustite, and bournonite.

STEPHANITE

Stephanite.—Sulphantimonite of silver; Ag_5SbS_4; Ag = 68·3, Sb = 15·4, S = 16·3.

Orthorhombic; symmetry, polar.

$$a : b : c = 0{\cdot}629 : 1 : 0{\cdot}685.$$

B = {010}, d = {021}, p = {111}, z = {112}, m = {110}, A = {100}, C = {001}.

Am (100) : (110) = 32° 10′, Cd (001) : (021) = 53° 52′, pm (111) : (110) = 37° 51′.

Twinned on (110). Cleavage {010}, {021}, imperfect. Brittle. Fracture, conchoidal. H = $2\frac{1}{2}$; G = 6·3. Iron-black. Streak, black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Freiberg** (Saxony).

Stephanite.—Brittle silver ore (Germ. *Schwarzgültigerz, Sprödglanzerz, Melanglanz*, Fr. *psaturose*). This mineral, which is important as an ore of silver, occurs in two habits, either as hexagonal prisms, or as flat hexagonal tables; in the latter, the prism-faces are very small or may be absent; the crystals are almost invariably terminated by the smooth basal plane. Some of the crystals are very rich in pyramid-faces. Twinning is constant and similar to that of aragonite, the mineral being pseudo-hexagonal; the crystals are usually traversed by twin-lamellæ parallel to the prism {110}, and the twin-junctions can be seen upon the basal plane. The polar character is only indicated by oblique striations upon the prism-faces, similar to those of pyrargyrite (Fig. 532). The striations also show many apparently simple crystals to be supplementary twins like those of hemimorphite (Fig. 242).

Though bright and lustrous when fresh, stephanite blackens like proustite on exposure to light. The best crystals occur at Freiberg, Saxony, both as prisms and as hexagonal plates with bevelled edges. Massive stephanite is worked on a large scale as an ore of silver in Nevada; stephanite and argentite being the chief ores of the famous Comstock Lode.

THE PYRARGYRITE GROUP

Pyrargyrite.—Sulphantimonite of silver; Ag_3SbS_3; Ag = 59·8, Sb 22·5, S = 17·7.

Hexagonal; symmetry, di-trigonal polar.

$$a = 104° 0′, \quad [a : c = 1 : 0{\cdot}789].$$

a = {10$\bar{1}$}, e = {110}, r = {100}, t = {310}, v = {20$\bar{1}$}, r' = {$\bar{1}$00}, u = {$\bar{2}\bar{1}\bar{1}$}, d = {$\bar{4}\bar{2}$3}.

ee (110) : (101) = 42° 5′, rr (100) : (010) = 71° 22′, vv (20$\bar{1}$) : (2$\bar{1}$0) = 35° 12′, vv (20$\bar{1}$) : ($\bar{1}$02) = 74° 25′.

Cleavage {100}, {110}, imperfect. Brittle. Fracture, conchoidal. H = $2\frac{1}{2}$; G = 5·8. Grey-black. Streak, purplish-red. Lustre, metallic-adamantine. Translucent. Refraction, very strong, ω = 3·084. Birefringence, negative, very strong; $\epsilon - \omega = -0{\cdot}203$. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Andreasberg** (Harz).

Proustite.—Sulpharsenite of silver; Ag_3AsS_3; Ag = 65·4, As = 15·2, S = 19·4. Hexagonal; symmetry, di-trigonal polar (?).

$$a = 103° 32', \quad [a : c = 1 : 0·804].$$

$$v = \{20\bar{1}\}, \quad a = \{10\bar{1}\}, \quad e = \{110\}.$$

ee (110) : (101) = 42° 46′, vv (20$\bar{1}$) : (2$\bar{1}$0) = 35° 18′, vv (20$\bar{1}$) : ($\bar{1}$02) = 74° 39′.

(Compare calcite, Figs. 588 and 590.)

Cleavage {100}, imperfect. Brittle. Fracture, uneven to conchoidal. H = 2½; G = 5·6. Scarlet-vermilion. Streak, scarlet. Lustre, adamantine. Sub-transparent. Refraction, very strong; $\omega = 2·979$. Birefringence, negative, very strong; $\epsilon - \omega = -0·268$. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Chañarçillo** (Chili).

This group, also known as the ruby silvers or red silver ores, includes **Pyrargyrite** (Germ. *Antimonsilberblende, dunkles Rothgültigerz*, Fr. *argyrythrose*).

Proustite (Germ. *Arsensilberblende, lichtes Rothgültigerz*).

The red silvers afford an excellent example of isomorphism; their angles are nearly identical, and they occur in very perfect crystals of similar habit.

Pyrargyrite is found mostly in prisms terminated by a low di-trigonal pyramid {310} (Harz), or by the drusy basal plane (Mexico); proustite almost always in prisms terminated by the di-trigonal pyramid {20$\bar{1}$} with small faces of the flat trigonal pyramid {110}. The lustrous specimens of this habit from Chañarçillo are among the most beautiful examples known of mineral crystallisation. That in the British Museum is one of the treasures of the collection.

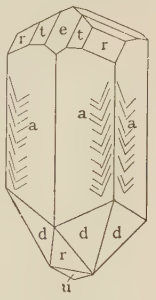


Fig. 532.—Pyrargyrite, a {10$\bar{1}$}, r {100}, t {301}, e {101}, d {4$\bar{2}$3}, r' {0$\bar{1}$0}, u {$\bar{1}$2$\bar{1}$}.

Both minerals twin according to several laws:

(1) Two prisms are juxtaposed at an angle of about 26°, a pair of faces a being common to both; they are related by rotation in the plane (211).

(2) Two prisms are juxtaposed at an angle of about 86°; here the relation is by rotation in the plane (100); these rectangular twins are common in proustite, but rare in pyrargyrite.

(3) Two hemimorphic prisms of pyrargyrite may interpenetrate with their principal axes parallel so as to resemble a single crystal belonging to the calcite class; these may be described as twinned by rotation in the plane (10$\bar{1}$); such twins are distinguished by the oblique striations on the prism-faces of the two crystals.

Doubly terminated crystals are extremely rare, but the polar character of pyrargyrite is always indicated by these striations on the prism-faces, which are not symmetrical towards the two ends (Fig. 532).

According to the transparency of its surface pyrargyrite varies in colour; the darkest specimens show a deep ruby gleam in thin splinters, but some appear almost as light as proustite. Proustite has always the same ruby-red colour when fresh, but on exposure to light its surface

becomes dead black, and specimens to be preserved must be kept covered. The two minerals may be safely distinguished by their streak.

Although the red silvers are obviously isomorphous, they rarely form mixtures; pyrargyrite generally contains some arsenic, but rarely as much as 3 per cent. The following analyses represent the greatest variations:

	S	Sb	As	Ag
Pyrargyrite—				
Andreasberg	17·81	22·45	...	59·75
Chañarçillo	18·17	18·47	3·80	60·53
Proustite—				
Chañarçillo	19·52	...	15·03	65·10
Saxony	19·54	3·74	12·29	64·43

Two very rare minerals, **pyrostilpnite** and **xanthoconite,** seem to have the same composition as pyrargyrite and proustite respectively, and to belong to the monoclinic system, so that the group is to be regarded as isodimorphous.

The red silvers are distinguished by their colour and streak from other minerals. Proustite when massive resembles cuprite, but is distinguished by its relative softness, and by the reactions for silver.

Some Noteworthy Localities:

Andreasberg (Harz).—Pyrargyrite in grouped crystals in which the flat hexagonal pyramid {210} projects; sometimes smooth, bright faces of {110} truncate its edges, and {100} appears on the corners. Generally twinned on (211). As a vein-mineral with calcite, arsenic, and sometimes harmotome.

Chañarçillo (Chili).—Beautiful prisms of proustite with di-trigonal terminations. These crystals are often coated with white asbestos, which can be stripped from the proustite and exposes the brilliant surface of the latter.

BOURNONITE

Bournonite.—Sulphantimonite of lead and copper; $PbCuSbS_3$; Pb 42·4, Cu = 13·0, Sb = 24·9, S = 19·7.

Orthorhombic.

$$a : b : c = 0·938 : 1 : 0·897.$$

A = {100}, B = {010}, C = {001}, *o* = {101}, *n* = {011}, *u* = {112}, *m* = {110}.

Am (100) : (110) = 43° 10′, *Bn* (010) : (011) = 48° 7′, *Co* (001) : (101) = 43° 43′, *Cu* (001) : (112) = 33° 15′.

Twinned on (110). Cleavage {010}, very imperfect. Brittle. Fracture, conchoidal to uneven. H = 2½; G = 5·8. Lead-grey. Streak, grey-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Neudorf** (Harz).

Bournonite (Germ. *Spiessglanzbleierz*) occurs in very beautiful crystals; a series of splendent groups from Herodsfoot Mine, near Liskeard, in

Cornwall, is to be seen in the British Museum ; and huge crystals from the Harz in the Berlin Museum. Bournonite was named after the mineralogist the Comte de Bournon. It is a mineral very rich in faces, generally tabular owing to the predominance of C, and having the edges and corners profusely modified. The prism-faces are vertically striated, the others smooth. The crystals are chiefly interesting on account of their twinning ; each of the crystallographic axes may be called an axis of pseudo-symmetry, the angles of the prism {110} as well as of the forms {101} and {011} being each nearly 90°, but twinning only takes place parallel to the faces of the prism {110}, of 86° 20′. Almost every crystal is a twin-group, or is traversed by a twin-lamella parallel to a face of the prism; repeated twinning gives rise to cruciform and stellar plates, and even to groups resembling cog-wheels, which are known at Kapnik, in Hungary, by the name of

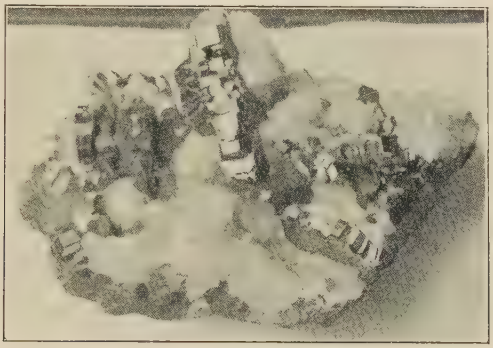


Fig. 533.—Bournonite on Quartz, from Liskeard (British Museum).

Rädelerz (or wheel-ore). Even massive bournonite may be distinguished by the eye from other grey sulphantimonites, such as fahlerz, owing to the twin-lamellæ, which can be discerned on a fractured surface. The composition is very constant, and the analyses do not generally indicate any isomorphous replacement of constituents, *e.g.* :

	S	Sb	Pb	Cu	As	Fe
Neudorf	19·63	25·68	41·38	12·68	...	...
Cornwall	20·30	26·30	40·80	12·70	...	...
„	19·36	23·57	41·95	13·27	0·47	0·68

In the last of these a little As seems to replace Sb.

Some Noteworthy Localities :

Neudorf (Harz). Tabular crystals with quartz, chalybite in brown rhombohedra {100}, and galena {111} with {311}, etc.

Herodsfoot Mine (Liskeard).—Twinned groups of short prisms united in wheel-shaped plates with uneven basal plane but brilliant prism-faces, on crystals of quartz. The re-entrant angles are formed by two faces of A {100}, and *o u* B *m n* are seen on the edges and corners (Fig. 533).

Kapnik (Hungary). —*Rädelerz* with quartz. The specimens often carry crystals of blende and tetrahedrite, together with pyrites and a little white clay. The bournonite is generally black, and only shows small faces of the domes and pyramids.

SURVEY OF THE SULPHANTIMONITES, ETC.

The sulphantimonites, sulpharsenites, and sulphobismuthites are commonly regarded as salts of sulpho-acids of the type $As(SH)_3$, or of others derived from these by the removal or addition of H_2S (*cf.* p. 234).

The normal sulpho-salts (orthosulpharsenites, etc.) will then be represented by the formula $R''_3As_2S_6$ or $3R''S \cdot As_2S_3$; to these belong:

Tetrahedrite	$3Cu_2S \cdot Sb_2S_3$	Cubic
Proustite	$3Ag_2S \cdot As_2S_3$	Hexagonal
Pyrargyrite	$3Ag_2S \cdot Sb_2S_3$	,,
Bournonite	$2PbS \cdot Cu_2S \cdot Sb_2S_3$	Orthorhombic

By some this is regarded as a dimorphous group analogous to the series of rhombohedral and orthorhombic carbonates $R''CO_3$, the corresponding angles being somewhat similar. But it may be questioned whether we are justified in looking upon $CaCO_3$ and Ag_3AsS_3 as similar compounds: moreover, aragonite twins on a prism of 63° 48′, whereas bournonite twins on a prism of 86° 20′.

Stephanite will be a salt of the acid $H_{10}Sb_2S_8$ or $5H_2S \cdot Sb_2S_3$, derived from the normal acid, $H_6Sb_2S_6$, by the addition of two molecules of H_2S.

The number of the sulpharsenites, etc., is very considerable, although many of the minerals are rare; they must be referred to no less than eleven different sulpho-acids.

A particularly well-defined isomorphous series is that of the following orthorhombic minerals included under the type $R''As_2S_4$ (metasulpharsenites, etc.):

Wolfsbergite	$Cu_2Sb_2S_4$	or	$Cu_2S \cdot Sb_2S_3$
Emplectite	$Cu_2Bi_2S_4$	,,	$Cu_2S \cdot Bi_2S_3$
Scleroclase	$PbAs_2S_4$	,,	$PbS \cdot As_2S_3$
Zinckenite	$PbSb_2S_4$	,,	$PbS \cdot Sb_2S_3$

All the minerals of this class possess metallic lustre and most are grey in colour; the sulpharsenites are more translucent than the sulphantimonites and sulphobismuthites; those which contain lead have the most brilliant metallic lustre. These minerals are somewhat difficult to distinguish, since the optical characters cannot be utilised, but for this purpose the streak is useful, and they may all be determined by pyrognostic tests.

Other noteworthy compounds of this class are **jamesonite,** $Pb_5Sb_6S_{14}$, a fibrous or acicular mineral with transverse cleavage, which sometimes occurs in sufficiently large masses to serve as an ore of lead; **lorandite,**

$TlAsS_2$, a rare mineral found in red crystals at Allchar, in Macedonia, almost the only prominent compound of thallium, of which element it contains no less than 59·4 per cent.

Among other sulpho-salts may be mentioned **argyrodite,** Ag_8GeS_6, a drusy mineral, found in the Freiberg silver mines and subsequently in Bolivia, in which germanium was discovered by Winkler in 1886; **cylindrite,** the representative of a small but curious class of compounds containing tin together with lead, antimony, and sulphur; this somewhat resembles graphite in appearance, and occurs in remarkable curvilaminar cylindrical forms in Bolivia, where several such sulpho-stannates containing silver are worked as ores of both tin and silver; another Bolivian mineral, **canfieldite,** $Ag_8(Sn,Ge)S_6$, a stanniferous argyrodite, is a link between these interesting minerals.

SECTION VIII

THE MONOXIDES

CUPRITE

Cuprite.—Oxide of copper; Cu_2O; Cu = 88·8, O = 11·2.

Cubic; symmetry, tesseral holoaxial. Common form, octahedron.

$$A = \{100\},\ o = \{111\},\ d = \{110\}.$$

Cleavage {111}, fair {100}. Brittle. Fracture, uneven. H = 3½; G = 6. Cochineal-red. Streak, brownish-red. Lustre, metallic-adamantine. Translucent. Refraction very strong; μ = 2·85. Fusible. Soluble in strong hydrochloric acid.

With the above description compare crystals from **Liskeard** (Cornwall).

Cuprite (Germ. *Rothkupfererz*).—This mineral, which is also known by the names of red copper ore or ruby copper, is found beautifully crystallised in lustrous octahedra, cubes, and combinations of these forms with {110} and {211}. The faces of the form {*hkl*} are very rare, and since this is the only form which differs from the corresponding holosymmetric form, the holoaxial symmetry is only displayed in a few crystals. Some specimens from Wheal Phœnix, near Liskeard, bear faces of {896} (Fig. 118), and others show faces of {13.10.12}. There is no other evidence of the true symmetry of the mineral, for etching figures appear to be holosymmetric, and the crystals do not rotate the plane of polarisation of plane-polarised light. The structure is also apparently holosymmetric (p. 296).

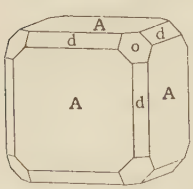


Fig. 534. — Cuprite, *A* {100}, *d* {110}, *o* {111}.

Twins of cuprite are unknown.

Massive cuprite somewhat resembles proustite in appearance, but is harder, and may be easily distinguished by the streak and blowpipe reactions. It occurs in sufficiently large quantities to be used as a profitable ore of copper.

Two curious varieties are the following:

(1) Chalcotrichite, a beautiful capillary form in which the slender fibres resemble the finest hairs, and are crystals elongated in the direction of a cube-edge. The most beautiful specimens of chalcotrichite hitherto

found are those from the old copper mines near **Gwennap** in Cornwall, and those found at **Morenci** in Arizona.

(2) Tile-ore (Germ. *Ziegelerz*), an earthy variety, of brick-red colour, totally unlike the crystallised mineral in appearance; this is often very impure and much darkened in colour by intermixture with earthy hæmatite, limonite, and other minerals.

Some Noteworthy Localities:

Liskeard (Cornwall).—Brilliant cubic combinations situated on vein-quartz whose cavities are lined with earthy limonite; the prominent faces are those of the cube and octahedron.

Gumeschevsk (Urals).—Crystals lining cavities in massive cuprite, which is often partially converted into malachite; the cuprite is either in octahedra, in octahedra with truncated edges, or in combinations of cubic habit (*cf.* Fig. 534).

Chessy (near Lyons).—Large octahedra and dodecahedra, often with truncated edges and corners, completely altered on the surface to a smooth green crust of malachite. These usually occur as isolated crystals embedded in a soft white clay (lithomarge), and are completely developed on all sides.

ZINCITE

Zincite.—Oxide of zinc; ZnO; Zn = 80·3, O = 19·7.

Hexagonal; symmetry, di-hexagonal polar. Cleavage, basal (perfect) and prism {10$\bar{1}$0}. Brittle. Fracture, sub-conchoidal. H = 4 to 4½; G = 5·6. Blood-red. Streak, orange. Lustre, sub-adamantine. Translucent. Refraction, strong, $\omega = 2{\cdot}01$. Birefringence, positive, $\epsilon - \omega = 0{\cdot}02$. Infusible. Soluble in hydrochloric acid.

With the above description compare crystalline material from **Franklin Furnace** (New Jersey).

Zincite is found as a deep red massive mineral, with a platy structure, at the zinc mines of Sterling Hill, New Jersey, U.S.A., where it is a valuable ore of zinc. Zincite may be recognised by its orange-yellow streak. Crystals are rare, and the form and symmetry were originally determined from the little white or yellow crystals of ZnO, which are occasionally formed by sublimation in the zinc-furnaces. Natural crystals have subsequently been found at Franklin Furnace, New Jersey, which have the same form (Fig. 535) as the artificial crystals.

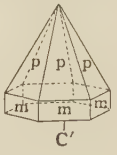


Fig. 535.—Zincite, p {10$\bar{1}$1}, m {10$\bar{1}$0}, C′ {000$\bar{1}$}.

Like wurtzite and greenockite, these are hexagonal (or di-hexagonal?) polar (compare the figures of greenockite on p. 80 and on p. 370). It is remarkable that these three substances, CdS, ZnS, and ZnO, possess not only the same symmetry and structure but nearly the same angles, the angle between the basal plane and pyramid of zincite being 61° 54′, the corresponding angle for wurtzite 62° 5′, and that for greenockite 61° 54′. The first two are undoubtedly

isomorphous in the ordinary sense, while zincite may be regarded as an example of an oxide isomorphous, if the term may be so used, or "isotypic," with the corresponding sulphide (and also with AgI), somewhat in the same way as $NaNO_3$ is related to $CaCO_3$.

MnO appears to enter into the composition of zincite as an isomorphous mixture, for some specimens contain as much as 7 per cent, and are then of a more yellow or orange colour, the uniformity of which, as described on p. 265, is evidence that the mixture is really homogeneous. From this it follows that MnO is probably dimorphous, since alone it forms octahedral crystals (manganosite). Zincite occurs at Sterling Hill with black franklinite and pale green willemite, producing a rock which is a curiously mottled mixture of minerals. Pyrognostic tests generally give reactions for manganese.

Anhydrous monoxides are rare in Nature, and do not fall into well-defined isomorphous groups, or graduate into isomorphous mixtures. MgO (**periclase**), MnO (**manganosite**), and NiO (**bunsenite**) have been found in octahedra. **Water** (ice) is a hexagonal mineral. The black oxide of copper (**tenorite** or **melaconite**), CuO, is found at Vesuvius in black scaly crystals somewhat resembling mica, and belonging to the anorthic system.

HYDRATED MONOXIDES

Brucite.—Hydrate of magnesium ; $Mg(OH)_2$; $MgO - 69{\cdot}1$, $H_2O - 30{\cdot}9$.

Hexagonal ; calcite class. Cleavage, basal {111}, perfect Sectile. Pliable. $H = 2\frac{1}{2}$; $G = 2{\cdot}4$. White. Streak, white. Lustre, waxy, pearly on (111). Translucent. Refraction, weak ; $\omega = 1{\cdot}559$. Birefringence, positive ; $\epsilon - \omega = 0{\cdot}020$. Infusible. Soluble in hydrochloric acid.

With the above description compare crystals from **Texas** (Pennsylvania).

Brucite is generally found with magnesite and dolomite in serpentine, as the result of the decomposition of magnesian silicates. It occurs in platy masses which somewhat resemble talc or gypsum in their softness, foliated structure, perfect cleavage and pearly lustre ; it is, however, easily distinguished by the optical characters, gypsum being biaxial and talc having negative birefringence.

In brucite the rings of the interference-figure show a peculiar and characteristic coloration, differing from that shown by most crystals or by Newton's rings ; the first ring is brownish-red on the inner and dull bluish on the outer side. As explained on p. 498, this is due to the fact that the birefringence varies for different colours.

Some brucite is green or blue in colour.

SECTION IX

THE SESQUI-OXIDES

THE CORUNDUM GROUP

Corundum.—Oxide of aluminium ; Al_2O_3 ; Al = 52·9, O = 47·1.

Hexagonal ; symmetry, di-hexagonal alternating (calcite class).

$$a = 85° 46', \quad [a : c = 1 : 1·363].$$

$$C = \{111\},\ R = \{100\},\ n = \{3\bar{1}1\},\ a = \{10\bar{1}\}.$$

$$RR\ (100) : (001) = 93° 56',\ Rn\ (100) : (3\bar{1}1) = 25° 59',\ CR\ (111) : (100) = 57° 34'.$$

Parting (but not true cleavage) {111}, {100}. Brittle. Fracture, conchoidal. H = 9 ; G = 4. Blue. Streak, colourless. Lustre, vitreous. Transparent. Dichroic. Refraction, strong ; $\omega = 1·768$. Birefringence, negative, weak ; $\epsilon - \omega = -0·008$. Infusible. Insoluble in acids.

With the above description compare crystals of sapphire from **Ceylon.**

Corundum (Germ. *Korund*, Fr. *corindon*) is well known in three of its varieties, ruby, sapphire, and emery.

Ruby and sapphire had attracted attention from the earliest times and were much prized as gemstones by the ancients, but Haüy was the first to refer them to the same species as the mineral which is now called corundum ; this had been brought from China and was known as " adamantine spar " on account of its hardness. This substance had been analysed by Klaproth in 1787, and was supposed by him to contain a new earth in addition to alumina. Haüy was led to class these minerals together on account of the similarity of their cleavage.

Subsequently it was found that ruby, sapphire, and corundum consisted merely of alumina with a slight intermixture of silica and ferric oxide. Ruby and sapphire had previously been united by Haüy under the name *télésie* (" the perfect substance ").

Corundum is rarely found well crystallised, but usually occurs as rolled and waterworn pebbles with other minerals in the gravel of river beds ; owing to their hardness, however, some of these retain their crystalline form and even possess sharply defined edges. The finest blue crystals come from Ceylon ; the best rubies come from Burma ; semi-opaque red and blue crystals are found in the dolomite near the St. Gothard.

Few minerals possess a greater variety of colour than corundum ; the common sorts are usually of a brown or reddish colour. Among those

clear and transparent crystals which are suited for gem stones, the following are distinguished by special names :

Ruby, red ; sapphire, deep blue to lilac ; oriental topaz, yellow and

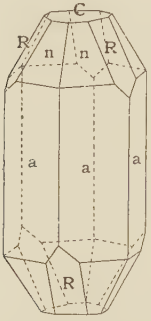


Fig. 536.—Corundum (sapphire), R {100}, *n* {3$\bar{1}$1}, C {111}, *a* {10$\bar{1}$}.

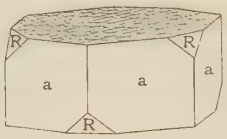


Fig. 537.—Corundum (ruby), *a* {10$\bar{1}$}, R {100}, C {111}.

brown ; oriental emerald, green ; oriental amethyst, purple. One variety, known as " Lux sapphire," is perfectly colourless.

The ordinary corundum is barely translucent ; the value of the transparent varieties depends upon their lustre and colour, and really fine pieces of good ruby of the peculiar colour known as " pigeon's blood " are even more highly prized than diamonds of the same weight.

Fig. 538.—Corundum from Ceylon.

The crystals of sapphire found in the gem-bearing sands and gravels are usually imperfect and more or less worn and rounded (Fig. 538) ; they are acute hexagonal bipyramids {13$\bar{1}$} or {15$\bar{3}$} (*cf.* p. 75), sometimes capped by {111} and with small faces of the rhombohedron {100} upon alternate edges of the pyramid (*cf.* Fig. 536). Crystals of ruby from Burma, and of sapphire from Montana, are tabular, owing to predominance of the basal pinakoid (Fig. 537). The basal planes are almost always traversed by a triangular system of striations due to lamellar twinning on the rhombohedron R {100} (twins of two distinct crystals juxtaposed according to this law like those of calcite also occur occasionally) ; the parting or apparent cleavage parallel to R seems to be due to this lamellar twinning, which may perhaps be in many cases secondary, and caused by pressure, planes parallel to R acting as glide-planes. The parting parallel to the basal plane appears to be due to incipient decomposition. Crystals of corundum often exhibit a pearly lustre on the base and a platy structure parallel to the same ; these are due to microscopic cavities produced along horizontal planes (111), which are therefore to be regarded as " solution-planes " along which

corrosion takes place most easily. Somewhat similar, though less distinct, is a third parting, parallel to the hexagonal prism $\{10\bar{1}\}$.

Cleavage-fragments of corundum with twin-lamellation resemble striated cubes and may be mistaken for a cubic mineral, since RR is near 90°; but the hardness is always sufficient to distinguish corundum from all other minerals; it is scratched by diamond alone.

Remarkable are the so-called "asteriated" or star-sapphires, which exhibit a six-rayed opalescent star when viewed nearly in the direction of the principal axis, a variety mentioned by Pliny. Such crystals are usually cut by jewellers with a curved surface (*en cabochon*) to display the effect. This "asterism" is due to minute tubular cavities arranged in planes parallel to the prism $\{10\bar{1}\}$, and caused by the same corrosion as the third parting mentioned above; it may be compared with the opalescent colours of orthoclase (moonstone), labradorite, and diallage.

Sometimes the corrosion-cavities of corundum are filled with decomposition-products, which give the crystals a bronzy submetallic lustre or sheen upon the basal plane.

Corundum is often, but not always, biaxial, the angle between the optic axes being small ($2V = 0°$ to $10°$); basal sections viewed between crossed nicols are seen to consist of six triangular sectors. Some authors, therefore, regard the crystals as triplets, and as really orthorhombic or even monoclinic; according to others the optical peculiarities may be explained as due to a laminar structure produced by secondary twinning on the planes R.

Corundum (even the clearest ruby or sapphire) generally contains a little ferric oxide, a little silica, and sometimes a trace of water, but otherwise consists simply of alumina. In the early analyses a considerable percentage of silica was found, but this may have been partly due to material abraded by the hard corundum from the agate mortar in which it was powdered.

The great differences in colour among the varieties of the gem stone, which have led to its receiving the names oriental amethyst,—topaz,—emerald, etc., are probably due to the ferric oxide, or to traces of chromium or manganese. Its value as a gem is chiefly due to the colour, and to the high refractive power which, as in many minerals, accompanies great density and hardness. The dichroism is sufficiently characteristic to be used as a means of identification; in ruby the colours seen in the dichroscope are deep red (*o*) and violet-red (*e*); in sapphire the colours are deep blue (*o*) and greenish or yellowish-blue (*e*).

Emery (Germ. *Smirgel*) is the name applied to the dark granular varieties of corundum so largely used as a polishing material; they consist usually of an intimate mixture of blue corundum with magnetite and also hæmatite; this material was formerly brought almost exclusively from the Island of Naxos or some of the neighbouring islands in the Grecian Archipelago, where it is found in a crystalline limestone, associated with schist and gneiss; it is now found in many places. A better polishing material is the massive variety of pure corundum, such as the compact purplish material formerly brought from Salem, Madras.

In many localities where it is found, corundum is accompanied by the aluminium hydrates, diaspore, hydrargillite, and bauxite ; it is sometimes converted into aluminous silicates, such as margarite and damourite. The best gem stones are found, as in Ceylon, in river gravels and sands, and not in their original matrix.

The artificial production of ruby has been a matter of great commercial interest ; crystallised corundum has now been manufactured in a variety of ways, and rubies made by Frémy's process (1877), or by allied methods, were actually used as gem stones. This method consists in the fusion of alumina, potassium carbonate, barium (or calcium) fluoride, and a little potassium chromate, the last being added in order to give a red colour to the crystals ; the mixture is maintained at a temperature of 1500° C. for several days, when the corundum solidifies as tabular crystals of ruby, having on their corners faces of the rhombohedron R (Fig. 537).

In a later method, due to Verneuil, by which considerable quantities of artificial ruby are produced, an oxyhydrogen blowpipe is directed downwards on to the apex of a refractory support and powdered alumina containing a little chromic oxide is fed downwards through the centre of the flame. The alumina is fused, and attaches itself to the support, building up a mass of considerable size resembling an inverted pear, which is in fact a single crystal often having its principal axis along the axis of the pear (though usually without faces). The broad end of the pear sometimes shows a drusy hexagonal pattern in accordance with the symmetry. Rubies thus produced closely resemble the natural stone in colour and pleochroism ; but when cut as gems they may usually be recognised by minute bubbles and curved striæ, which are seldom entirely absent.

Some Noteworthy Localities :

Burma.—At Mogok, in the neighbourhood of Mandalay, ruby occurs in a crystalline limestone, together with spinel, pyrrhotite, graphite, phlogopite, etc.

The crystals, rarely well developed, are a combination of basal pinakoid and rhombohedron like the artificial crystals ; both the ruby and spinel are corroded, the former along the rhombohedron faces.

Campolongo, Ct. Tessin, Switzerland.—Opaque red or blue crystals, generally very imperfect, but sometimes in prisms terminated by pyramid faces, occur in the white dolomite. Associated with them are silvery mica, diaspore, and green tourmaline.

Thibet.—Large irregular pyramids, like Fig. 538, said to come from Thibet, are of a brown colour, and show a remarkable bronzy lustre and hexagonal banding on the basal plane—both due to the corrosion described above.

Hæmatite.—Oxide of iron ; Fe_2O_3 ; Fe = 69·9, O = 30·1.

Hexagonal ; symmetry, di-hexagonal alternating (calcite class).

$$a = 85° 42', \quad [a : c = 1 : 1·3656].$$

$$r = \{100\},\ C = \{111\},\ n = \{3\bar{1}1\},\ u = \{211\},\ e = \{110\},\ a = \{10\bar{1}\}.$$

$$rr\ (100) : (010) = 94° 0',\ rn\ (100) : (3\bar{1}1) = 26° 0'.$$

Cleavage (parting), *r*, C, imperfect. Brittle. Fracture, uneven. H = 6; G = 5·2. Iron-black, blood-red when translucent. Streak, brownish-red. Lustre, metallic. Nearly opaque. Fusible with difficulty. Soluble in hydrochloric acid.

With the above description compare crystals from **Elba.**

Hæmatite, specular iron, micaceous iron ore, iron-glance (Germ. *Eisenglanz*, Fr. *fer oligiste*), a very important ore of iron, is isomorphous with corundum. The name hæmatite is as old as Theophrastus and Pliny, and denotes the blood-red colour of some of the ordinary massive varieties; but the mineral when crystallised is of a totally different appearance, and to this the names specular iron and iron-glance refer. The crystals are often brilliant steely plates with modified edges, as shown in Fig. 540. But the finest crystals, those from the iron mines of the Island of Elba, are stout combinations of rhombohedra *r*, *u*, with the hexagonal bipyramid *n* {3$\bar{1}$1}. A typical combination is shown in Fig. 539. In these the obtuse

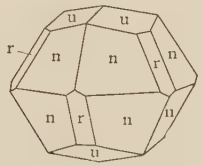


Fig. 539.—Hæmatite, *n* {3$\bar{1}$1}, *u* {211}, *r* {100}.

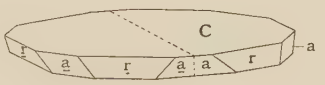


Fig. 540.—Hæmatite, twin-crystal, united along ($\bar{1}\bar{1}$2).

rhombohedron *u* may be recognised by its horizontal striations and convex surface.

The tabular crystals are more common in other localities; their tendency to form rosette-shaped groups (Germ. *Eisenrosen*) has been mentioned and illustrated on p. 307. Fig. 541 is from a photograph of a hæmatite rosette. Twin-crystals are not rare among the crystals of rhombohedral habit in which two individuals interpenetrate by hemitropy about the principal axis or by reflection over (2$\bar{1}\bar{1}$); in the crystals of tabular habit, two plates overlap or interpenetrate, but sometimes the two individuals unite with plane of composition parallel to the prism (2$\bar{1}\bar{1}$) so as to form a single plate, as shown in Fig. 540. Fine lamellæ parallel to the rhombohedron *r*, as in corundum, indicate lamellar twinning (possibly secondary) parallel to {100}; as in corundum, this twinning gives rise to a parting parallel to *r*, which must not be confused with a true cleavage. A further resemblance to corundum is supplied by a second parting parallel to the base C {111}, which is also due to a lamellar structure.

Hæmatite is one of the few minerals in which the electric conductivity in different directions has been accurately measured. The surface of electric conductivity (constructed like the surface of thermal conductivity, p. 120) is found to be an ellipsoid of revolution in accordance with the hexagonal symmetry. The conductivity is about twice as great in the horizontal as in the vertical direction.

In very thin flakes, such as can sometimes be found under the microscope, the mineral is seen to be really blood-red by transmitted light.

Very thin scaly varieties of hæmatite are red and quite soft, and adhere to the fingers like graphite when touched.

Common massive hæmatite, known by the name of red hæmatite, is brownish-red in colour, generally possesses a fibrous structure, which is cut transversely by a curvilaminar banding, and the surface is often botryoidal or reniform (*cf.* Fig. 455, p. 311). The botryoidal masses with radial-fibrous structure, common in Cumberland, break up into conical forms known there as "pencil-ore." Compact hæmatite has been used in ancient and modern times and in many parts of the world for ornamental purposes.

Earthy hæmatite, red ochre, or reddle is a light-red earthy material generally mixed with clay.

Some iron ore, *e.g.* that of the Lake Superior region and of Cumberland, consists mainly of hæmatite.

In some of its modifications hæmatite may resemble limonite or some other hydrate of iron, but the red or reddish-brown streak serves to distinguish it from such minerals, whose streak is in general brown.

Some Noteworthy Localities :

Cumberland and **Lancashire.**—Specular iron ore occurs in the iron mines of Cleator Moor in splendent black plates, so grouped upon rock crystal as to present a velvety appearance ; the plates have their edges formed by the rhombohedron *r*, and are sometimes slightly convex. The massive mineral from these counties is the typical red hæmatite and pencil ore mentioned above ; its surface is often transformed into black limonite ; the best specimens are from Ulverstone. The iron ores here fill fissures and cavities in the carboniferous limestone.

St. Gothard (Switzerland). -Tabular crystals grouped into "*Eisenrosen*" ; these are sometimes stout tables bounded by the hexagonal prism ; they are associated with adularia, often twinned, as in Fig. 659 of orthoclase, p. 515, and with rock crystal or smoky quartz, muscovite, etc., lining cavities in gneiss and granite.

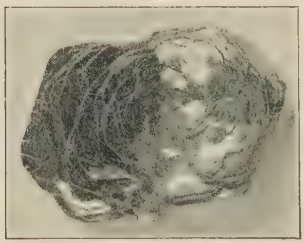


Fig. 541.—Hæmatite from St. Gothard.

Island of Elba.—The stout rhombohedral crystals of Fig. 539 occur under the conditions described on p. 379. The hæmatite is often brilliantly tarnished.

Vesuvius. — Small brilliant crystals of hæmatite line cavities in a trachytic lava, where they appear to have been formed by the action of vapours (perhaps ferric chloride and steam) ; these crystals are usually platy and skeletal.

Hæmatite and corundum are clearly isomorphous, although in Nature they scarcely enter into isomorphous mixture ; and artificially prepared Ti_2O_3 and Cr_2O_3 are isomorphous with them. The former compound probably enters into the constitution of many hæmatites which are

titaniferous ; the rosette crystals of St. Gothard contain about 6 per cent of titanium. There is, however, also a mineral known as ilmenite (see p. 491), containing up to about 30 per cent of titanium, which has also been regarded as an isomorphous mixture of Fe_2O_3 and Ti_2O_3 and placed in the corundum group, but which contains also a considerable proportion of FeO.

Ilmenite is found in well-defined crystals in the diorite of Kragerö in Norway, and at other localities, and crystallises in the hexagonal system with angles very near those of hæmatite, but with the hexagonal alternating symmetry of the dioptase class. It has been argued that in respect of this reduction of symmetry ilmenite, as compared with hæmatite, is analogous to dolomite, as compared with calcite.

Some varieties of ilmenite, however, contain very little Fe_2O_3 but a large proportion of FeO, while others again contain MgO ; and analysis has shown that these correspond to the formula $R''TiO_3$, where R″ denotes Fe and Mg capable of replacing one another. The mineral should then be regarded as a titanate of magnesium and iron, an isomorphous mixture of $MgTiO_3$ and $FeTiO_3$, and finds its place among the silicates and titanates, where it apparently belongs to the same isomorphous group with the mineral pyrophanite, $MnTiO_3$ (p. 492). Nevertheless these minerals certainly have angles nearly identical with those of hæmatite, and the " isomorphism " of the two groups may be compared with that of zincite and wurtzite, mentioned on p. 401.

THE HYDRATED SESQUI-OXIDES

Limonite.—Hydrate of iron ; $2Fe_2O_3 . 3H_2O$ (?) ; $Fe_2O_3 = 85{\cdot}5$, H_2O 14·5. Amorphous. Fracture, uneven to fibrous. $H = 5\frac{1}{2}$; $G = 3{\cdot}8$. Dark brown. Streak, yellowish-brown. Lustre, submetallic. Opaque. Fusible with difficulty to a magnetic bead. Soluble in hydrochloric acid.

With the above description compare botryoidal masses from **Lostwithiel** (Cornwall).

Göthite.—Hydrate of iron ; $Fe_2O_3 . H_2O$, or $FeO(OH)$; $Fe_2O_3 = 89{\cdot}9$, $H_2O = 10{\cdot}1$.

Orthorhombic.

$$a : b : c = 0{\cdot}918 : 1 : 0{\cdot}607.$$

$$(110) : (1\bar{1}0) = 85° 8', \ (011) : (0\bar{1}1) = 62° 30'.$$

Cleavage {010}, perfect. Brittle. Fracture, uneven. $H = 5$; $G = 4{\cdot}2$. Blackish-brown. Translucent. Refraction, very strong ; $\beta = 2{\cdot}5$. Birefringence, negative. Axial plane for red (100), for green (001). Acute bisectrix perpendicular to (010). $2E = 58\frac{1}{2}°$ (red). Pleochroic. Fusible with difficulty to a magnetic bead. Soluble in hydrochloric acid. Weakly magnetic.

With the above description compare crystals from **Lostwithiel** (Cornwall).

Manganite.—Hydrate of manganese ; $Mn_2O_3 . H_2O$, or $MnO(OH)$; $Mn_2O_3 = 89{\cdot}8$, $H_2O = 10{\cdot}2$.

Orthorhombic.

$$a : b : c = 0{\cdot}844 : 1 : 0{\cdot}545.$$

$$(110) : (1\bar{1}0) = 80° 20', \ (011) : (0\bar{1}1) = 57° 10'.$$

Twinned on (011). Cleavage, {010} perfect, {110} imperfect. Brittle. Fracture, uneven. H = 4; G = 4·4. Steel-grey. Streak, reddish-black. Lustre, metallic. Opaque. Infusible. Soluble in hydrochloric acid with evolution of chlorine.

With the above description compare crystals from **Ilfeld** (Harz).

A number of hydrates of iron and of aluminium are mentioned in the table on p. 605.

Among these **limonite** is the most common; it is a very frequent product of the decomposition of other iron minerals and often occurs as a brownish-black amorphous crust upon their surface: it is also frequently found as a "pseudomorph" after minerals containing iron. Thus brown or black crystals having the form of iron-pyrites, magnetite, or chalybite, and preserving all their original sharpness of outline, sometimes consist entirely of limonite; otherwise the mineral is stalactitic, botryoidal, or earthy—never crystallised; it is often black and glazed on the surface, and from this character derives one of its names, "stilpnosiderite." The name limonite (*λειμών*, a meadow) really refers to "bog-iron ore," which is a brownish-yellow deposit common in marshes, and derived from the ferrous carbonate and sulphate dissolved in their waters; this often coats or replaces decaying vegetable matter; and it forms the iridescent slime common in marshy pools.

In **Sweden** the limonite forms large concretionary masses at the bottom of lakes (Swed. *Sjömalm*), and is worked as an ore of iron; when the concretions are small spherical nodules the ore is known as "pea-iron" (Germ. *Bohnerz*). Limonite can generally be recognised and distinguished from other hydrates of iron by its brownish-yellow streak and hardness of 5; but these amorphous and somewhat ill-defined hydrates pass into each other and frequently occur together as decomposition products of iron minerals. They probably consist of colloidal ferric oxide, with varying amounts of water: $Fe_2O_3 + xH_2O$. Typical limonite approximates to $2Fe_2O_3 . 3H_2O$.

The brown cellular quartz known in Cornwall as "gossan" (Germ. *eiserner Hut*, Fr. *chapeau de fer*), which often constitutes the outcrop of metalliferous veins, and is regarded as an indication of their existence below the surface, contains earthy minerals consisting largely of ferric hydrates as decomposition products of iron-pyrites; such hydrates, together with hæmatite, account for the prevalent red and yellow colour of most rocks and mineral specimens which contain iron compounds.

Among the ferric hydrates, **göthite**, FeO(OH), is conspicuous as a crystallised mineral which is found in lustrous black or brown orthorhombic prisms with pyramidal terminations and pinakoidal cleavage (010). Cleavage-flakes show strong pleochroism, and in convergent light a negative bisectrix with the axial planes for red and green at right angles, as in brookite.

Some of the finest specimens were found in the iron mines of Lostwithiel, in Cornwall. The delicate radial groups of acicular crystals from Przibram in Bohemia have quite a velvety appearance (Germ. *Sammetblende*).

Another mineral having the same composition, known as **lepidocrocite,** occurs in fine red-brown micaceous scales (Germ. *Rubinglimmer*). These are also orthorhombic, but differ from göthite in their angles and optical properties. They form one of the common alteration-products which line secondary cavities along solution-planes in decomposing minerals and sometimes give them a bronzy sheen (*e.g.* hypersthene, p. 481). The scales can be recognised under the microscope and distinguished from hæmatite by their extinction and pleochroism, since the scales of the latter mineral are basal pinakoids of a hexagonal mineral and therefore isotropic and not pleochroic.

To the same group with göthite belong **diaspore,** AlO(OH) and **manganite,** MnO(OH). Diaspore is generally a white, cleavable, scaly, brittle mineral, sometimes of talcose appearance, which may be recognised as an alteration product of alumina, since it is generally found accompanying corundum and emery, and as a coating on crystals of corundum. It can be distinguished from gypsum, talc, and brucite by its superior hardness ($H = 6\frac{1}{2}$); the cleavage-flakes {010} are perpendicular to the third mean line, and the birefringence is strong. Manganite (Fr. *acerdèse*) occurs in steel-grey crystals of metallic lustre ($H = 4$), which are prisms with obtuse terminations, vertically striated, and frequently twinned; the specimens from Ilfeld, in the Harz, are very fine. When the crystals are soft, this is due to their dehydration and partial conversion into the earthy oxide, pyrolusite, MnO_2.

Among the aluminium hydrates, **bauxite,** $Al_2O_3 . 2H_2O(?)$, a white, brown or red, massive, concretionary, or earthy mineral, is of importance as one of the best ores of aluminium; the name is derived from Baux, near Arles, in France, where the mineral was first found.

With the exception of göthite, lepidocrocite, diaspore, and manganite, all these hydrated minerals are amorphous and colloidal, containing varying proportions of water and often other adsorbed substances.

SECTION X

THE DIOXIDES

THE CASSITERITE GROUP

Cassiterite.—Oxide of tin; SnO_2; Sn = 78·8, O = 21·2.

Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}672.$$

$s = \{111\}$, A = {100}, $m = \{110\}$, $e = \{101\}$, $h = \{210\}$, $z = \{321\}$.

ss (111) : $(1\bar{1}1) = 58°\ 19'$, ms (110) : (111) = 46° 27′.

Twinned on {101}. Cleavage {110}, imperfect. Brittle. Fracture, subconchoidal. $H = 6\frac{1}{2}$; G = 7·0. Brown. Streak, grey. Lustre, adamantine. Translucent. Refraction, very strong; $\omega = 1{\cdot}997$. Birefringence, positive, strong; $\epsilon - \omega = 0{\cdot}097$. Infusible. Insoluble in acids. With soda on charcoal, yields tin.

With the above description compare crystals from **St. Agnes** (Cornwall).

Cassiterite or tinstone (Germ. *Zinnstein*, Fr. *étain oxydé*) is almost the only ore of tin, and is named from the Greek word for that metal.

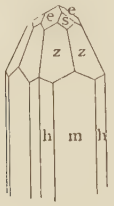


Fig. 542.—Cassiterite, *m* {110}, *h* {210}, *s* {111}, *e* {101}, *z* {321}.

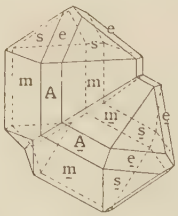


Fig. 543.—Cassiterite, *m* {110}, A {100}, *s* {111}, *e* {101}, twinned on $(01\bar{1})$.

Good crystals are comparatively rare, but the density and hardness, and the adamantine lustre of the crystal-faces, even when they are imperfect, serve to distinguish the mineral. Simple crystals are unusual; where they occur they may be of two types, either stout square prisms terminated by the faces *s*, *e* (Fig. 543), or slender prisms terminated by acute pyramid faces (Fig. 542); the latter ("needle-tin") are comparatively rare; in Cornwall, where very acute crystals of this type (with {321} and {521}) used to be found in the tin mines of the Camborne district, they were known

as "sparable tin" from their resemblance to "sparable (sparrow bill ?) nails"; the apex of the pyramidal termination is only very rarely truncated by the basal plane. Other prism-faces occur, and this zone is vertically striated; the striations will help the student to identify the prism-zone on twin-crystals, which are very frequent and not easy to decipher; they are, as shown in Fig. 543, of the first habit; the plane (101) of twinning and combination can generally be located by a re-entrant angle at the corner of the knee-shaped doublet; it is this corner which generally protrudes from the specimen.

Repetition of the twinning upon different faces of the form {101} is very common, and leads to a succession of these knee-shaped corners in which the two striated prism-zones meet at angles of 67° 50′ (Fig. 544).

Cassiterite usually contains Fe_2O_3, to which, as well as to other impurities (Ta_2O_5, etc.), its varying shades of colour are no doubt due; some cassiterite from the Malay peninsula is almost colourless, some from New England, in Australia, is a ruby red, some from Mexico is yellow; there are even specimens in the British Museum of transparent cassiterite facetted as a gem; the lustre and hardness would fit this mineral for a gem stone were it more often transparent. Most cassiterite is almost black. Among the massive varieties the so-called "wood-tin" (Germ. *Holz-zinnerz*) is remarkable as a dull mineral of wooden appearance, which possesses none of the adamantine lustre of the crystals; it is botryoidal, with a radiated fibrous structure, consisting of concentric curvilaminar layers, usually of different shades. "Toad's-eye tin" is a Cornish name for little brown-banded spherical nodules with the same radial-fibrous structure.

Fig. 544.—Cassiterite, twin group (Oxford Museum).

Owing to its hardness, density, and resistance to solvents, cassiterite is one of the minerals which are not only mechanically concentrated by the action of running water, but remain unaltered in alluvial deposits in the form of pebbles or sand. It is then commonly known as "stream tin." This has been worked as an ore in Cornwall, where the finely divided cassiterite from old workings sometimes accompanies vegetable and animal remains. Stream tin is worked on a large scale in the Malay peninsula and in Australia.

Specimens from the typical localities in all collections illustrate the peculiar associations of cassiterite; it is found lining cavities in gneiss and granite or rocks accompanying them, and is associated with apatite, zinnwaldite, topaz, tourmaline, and fluor, together with quartz, wolframite, axinite, scheelite, and beryl; the almost invariable presence of some of the five first-mentioned fluorine minerals has led many (following Daubrée) to believe that the contents of these cavities and veins are due

to the action of gaseous compounds of fluorine (and boron). In support of this theory experiments made by Daubrée showed that cassiterite can be artificially produced by the action of steam on the vapour of chloride or fluoride of tin; moreover, the granite is sometimes altered into "greisen," a mixture of quartz and mica impregnated with topaz, cassiterite, tourmaline, and fluor.

Beautiful artificial crystals of cassiterite have been described, which are formed in the tin works by quite a different process, namely, the oxidation of metallic tin; these are of a violet colour and are not twinned, whereas twinning is almost universal in natural occurrences of the mineral.

There is, however, evidence that cassiterite may also have been deposited from solutions; it is found impregnating and even replacing organic remains, and near Penzance a tin ore was formerly worked consisting of chlorite nodules cemented together by cassiterite.

Some Noteworthy Localities:

St. Agnes (Cornwall).—In the mines of this and other Cornish districts cassiterite occurs in quartzose lodes both in the granite and slate, near their junction; the veinstuff is a mixture of cassiterite and quartz, and the crystals, mostly of grey and brown colour, are generally the twins of Fig. 543, recognisable by the re-entrant angles.

Erzgebirge.—Beautiful specimens come from the tin mines on the northern (Saxon) and southern (Bohemian) sides of this range. At Zinnwald in Saxony and at Zinnwald and Schlaggenwald in Bohemia the cassiterite occurs near the contact of the granite with the slate, either as an impregnation in greisen, or in fine black twinned crystals in veins of the granite associated with zinnwaldite, topaz, apatite, quartz, fluor, and molybdenite. Portions of the greisen consist entirely of a granular mixture of cassiterite and topaz.

Rutile.—Oxide of titanium; TiO_2; Ti = 60·0, O = 40·0.
Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}644.$$

$$m = \{110\},\ A = \{100\},\ l = \{310\},\ s = \{111\},\ e = \{101\}.$$

$ss\ (111) : (1\bar{1}1) = 56°\ 52',\ ee\ (101) : (\bar{1}01) = 65°\ 35',\ ms\ (110) : (111) = 47°\ 40'.$

Twinned on {101}. Cleavage {100}, {110}, good. Brittle. Fracture, uneven. H = 6½; G = 4·3. Colour, reddish-brown. Streak, yellowish-brown. Lustre, metallic-adamantine. Translucent. Refraction, very strong; $\omega = 2{\cdot}616$. Birefringence, very strong, positive; $\epsilon - \omega = 0{\cdot}287$. Infusible. Insoluble in acids.

With the above description compare crystals from **Alexander County** (North Carolina).

Rutile, the chief native compound of titanium, belongs to the same natural group with cassiterite, which it resembles closely in crystalline form and twinning, as well as in structure. The larger crystals, usually found in cavities in granite and the crystalline schists, or in quartz, can be easily recognised as striated prisms terminated, like cassiterite, by *s* and *e*, as in

Fig. 543. Lamellar twins formed by repeated twinning on parallel faces, as in aragonite, are common. Triplets, as shown in Fig. 545, due to repetition of the twinning upon different faces of the form, are even more frequent than in cassiterite. Sometimes (as at Graves Mountain, Georgia) the twinning is repeated in such a manner that the twin group returns upon itself and makes a complete ring, as shown in Fig. 546, where the eight individuals do not lie in a plane, but are inclined to each other at 65° 35′ in a zigzag manner. Sometimes, as shown in Fig. 251, p. 103, twin groups of acicular rutile form a reticulated skeletal plate, in which the rays meet at this angle ; delicate examples are found at Tavetsch in Switzerland. Such reticulations are called "sagenite," from σαγήνη, a net.

The characteristic heart- and knee-shaped (or kite-shaped) forms due to this twinning (and also to twinning on {301}) afford means of recognising rutile under the microscope ; it has been frequently identified as microscopic crystals in many slates. Rutile is one of the heavy unalterable minerals which are found as grains and pebbles, in gravels ; it may be

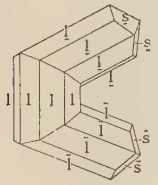


Fig. 545.—Rutile, *l* {310}, *s* {111} ; Triplet twinned on faces of {011}.

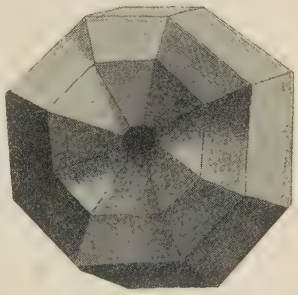


Fig. 546.—Rutile from Georgia ; Octet twinned on faces of {011}.

almost black, but is then recognisable among other black minerals by the prismatic cleavages combined with the peculiar lustre.

In acicular crystals, which are by no means rare, rutile appears pale yellowish-red, and presents quite a different aspect from the ordinary black or reddish masses or the brilliant metallic crystals in which it is sometimes found. Pieces of rock crystal, or smoky quartz containing fine rutile fibres known as *flèches d'amour* (Fig. 547), are polished as ornaments ; the latter were described by Pliny under the name *Veneris crinis :—Nigerrimi nitoris continet speciem rufi crinis.*

The curious manner in which rutile needles are symmetrically disposed on hexagonal plates of hæmatite (from the St. Gothard) has been shown in Fig. 227, p. 96.

Massive rutile, in reddish-black masses, is largely worked at Risör and other places in Norway as an ore of titanium, which is used for colouring glass yellow.

To the same group with rutile and cassiterite belong **polianite,** MnO_2, a steel-grey mineral occurring in small crystals with and closely resembling

the more common hydrate manganite, and **plattnerite,** PbO_2, a rare black massive mineral which is sometimes found in microscopic crystals. To the cassiterite group is added by many authors the zirconium silicate, zircon, $ZrSiO_4$ (together with thorite, the corresponding thorium silicate, which is isomorphous with it) ; in its angles and its twinning, as well as in its structure, zircon closely resembles cassiterite, and this is another case of "isomorphism" between bodies which are chemically unlike, *i.e.* the minerals are "isotypic."

In rutile and cassiterite the Ti, or Sn, atoms form a centred tetragonal lattice, Fig. 410 (v), while the oxygen atoms lie in the horizontal planes through the Ti or Sn atoms, two oxygens forming a pair about each of

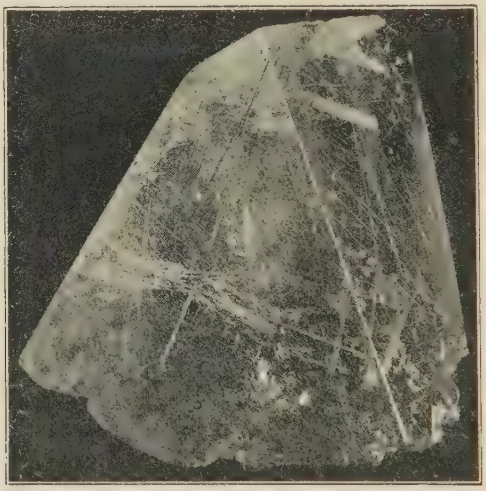


Fig. 547.—Rutile in Quartz.

these, lying in one or other of the two diagonal planes of the prism, alternately, in the successive horizontal planes.

In zircon the group of atoms $ZrSiO_4$ corresponds to the group Ti_2O_4, which is the unit cell of the structure of rutile, a simple tetragonal lattice of zirconium being centred by one of silicon (and *vice versa*).

An equal, and still more remarkable, similarity in form and structure exists between these minerals and the yttrium phosphate, xenotime, in which the atoms (though different in valency and in chemical character) are arranged in the same manner as those of zircon.

ANATASE AND BROOKITE

Among the dioxides of tetravalent elements occurs a remarkable case of polymorphism: TiO_2 is found as no less than three well-defined and beautifully crystallised minerals, rutile, anatase, and brookite.

Anatase.—Oxide of titanium ; TiO_2 ; Ti = 60·0, O = 40·0.
Tetragonal.

$$a : c = 1 : 1·777.$$

$p = \{111\}$, C = {001}, $e = \{101\}$, $v = \{117\}$, A = {100}.

pp (111) : $(1\bar{1}1) = 82° 9'$, vv (117) : $(1\bar{1}7) = 27° 39'$.

Cleavage C, p, good. Brittle. Fracture, sub-conchoidal. H = $5\frac{1}{2}$; G = 3·9. Brownish-yellow. Streak, colourless. Lustre, metallic-adamantine. Translucent. Refraction, very strong ; $\omega = 2·554$. Birefringence, strong, negative ; $\epsilon - \omega = -0·061$. Infusible. Insoluble in acids.

With the above description compare crystals from **Bourg d'Oisans** (Dauphiné).

Brookite.—Oxide of titanium ; TiO_2 ; Ti = 60·0, O = 40·0.
Orthorhombic.

$$a : b : c = 0·841 : 1 : 0·944.$$

A = {100}, $l = \{210\}$, $m = \{110\}$, B = {010}, $x = \{102\}$, $y = \{104\}$, $z = \{112\}$, $n = \{121\}$, $e = \{122\}$, $o = \{111\}$, $t = \{021\}$.

mm (110) : $(1\bar{1}0) = 80° 10'$, ee (122) : $(\bar{1}22) = 44° 23'$.

Cleavage, B, m, C, imperfect. Brittle. Fracture, conchoidal. H = $5\frac{1}{2}$; G = 4. Red. Streak, grey. Lustre, metallic-adamantine. Translucent. Refraction, very strong ; $\gamma = 2·74$, $\beta = 2·59$ (Na). Birefringence, very strong, positive ; $\gamma - \alpha = 0·16$ (Na). Dispersion of optic axes very strong. Acute bisectrix normal to A for all colours. Axial plane (010) for blue, (001) for red light. 2E = 30° (yellow). Uniaxial for a colour between yellow and green. Infusible. Insoluble in acids.

With the above description compare crystals from **Tremadoc** (North Wales).

Anatase, or octahedrite, like rutile, is tetragonal, but its angles are not those of rutile, nor can it be referred to the same axes. The structure also is quite different. The name was given by Haüy from the Greek ἀνάτασις,

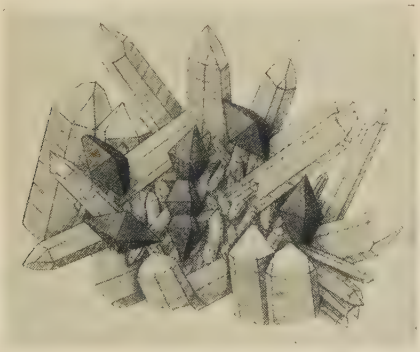


Fig. 548.—Anatase with Quartz, from Bourg d'Oisans.

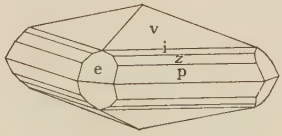


Fig. 549.—Anatase, v {117}, i {116}, z {113}, p {111}, e {101}.

erection, to indicate that the c-axis is longer than that of rutile. The common habit is the simple steep bipyramid of Fig. 548. A second habit is the flatter one of Fig. 549, in which, referred to the above axes, the faces have the following indices, $v = \{117\}$, $i = \{116\}$, $z = \{113\}$, $p = \{111\}$, $e = \{101\}$.

Anatase has a metallic-adamantine lustre even superior to that of rutile, and is only found in isolated crystals. The steep bipyramidal crystals (Fig. 548) are usually black or bluish, and appear opaque, although cleavage-plates may be transparent. The apparent opacity is due to the high refractive index, which in crystals of this form causes total reflection.

Brookite belongs to the orthorhombic system. Like anatase, it is found almost solely in brilliant crystals with metallic-adamantine lustre, and occurs in two distinct habits—(1) the thin tabular crystals of Fig. 550 (found in cavities in diabase near Tremadoc, North Wales); these have the large macro-pinakoid A vertically striated and are terminated by brilliant faces; (2) the crystals of Fig. 551, resembling six-sided bipyramids; these are a combination of {110} and {122}; large black crystals of this type have been found in the elæolite-syenite of Magnet Cove, Arkansas, and are called "arkansite."

The Tremadoc crystals, when very thin, are of a bright red colour by

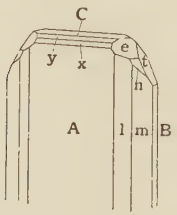


Fig. 550.—Brookite, A {100}, B {010}, C {001}, *m* {110}, *l* {210}, *y* {104}, *x* {102}, *e* {122}, *t* {021}, *n* {121}.

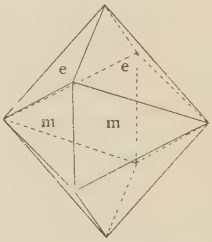


Fig. 551.—Brookite (Arkansite), *e* {122}, *m* {110}.

transmitted light, and, being transparent, are excellently adapted to show the peculiar crossing of the optic axial planes for different colours described on p. 178. The acute bisectrix for all colours is perpendicular to A {100}, but the axial plane for red light is horizontal, while that for blue light is vertical. If any such crystal of brookite placed between crossed nicols on the microscope stage be viewed through a spectroscope, a black band will be seen in the green part of the spectrum corresponding to the light for which the mineral is uniaxial.

There is a slight difference in the specific gravity of the three modifications of TiO_2—rutile, 4·2; anatase, 3·9; brookite, 4·0. All three modifications have been produced artificially in a manner similar to that mentioned on p. 414 as the process by which cassiterite has been obtained, the action of steam on fluoride of titanium; the three modifications are obtained at different temperatures, rutile being formed at the highest, anatase at the lowest temperature. Rutile appears to be the most stable of the three, for aggregates of rutile needles in the form of brookite (Fig. 551) have been found at Magnet Cove, and in the form of anatase in Brazil.

It is remarkable that wherever one of these minerals is found it is accompanied by one or both of the others; brookite, for example, occurs

with anatase at Tremadoc, with rutile at Magnet Cove. This is not at all usual with polymorphous compounds.

The only other metallic dioxide of at all frequent occurrence is **pyrolusite,** MnO_2, a soft, black, amorphous mineral (H = 2), which is largely worked as an ore of manganese; it appears to be usually a result of the dehydration of manganite, and crystals which have been regarded as pyrolusite are probably pseudomorphs after manganite; true crystals of MnO_2 have been distinguished above as polianite.

HYDRATED DIOXIDES

Psilomelane.—Hydrate of manganese (barium, potassium, etc.).

Amorphous. Fracture, smooth. H = 5½; G = 4·2. Black. Streak, brownish-black. Lustre, submetallic. Opaque. Fusible with difficulty. Soluble in hydrochloric acid with evolution of chlorine.

With the above description compare botryoidal masses from **Lostwithiel** (Cornwall).

No crystalline hydrates of the dioxides are known among minerals, but a black *amorphous* hydrate of manganese occurs, known as **psilomelane.** This is usually botryoidal or stalactitic, and may be distinguished from most minerals of similar appearance by its superior hardness; the streak distinguishes it from limonite. Psilomelane contains variable proportions of barium, potassium, and sodium, with from 3 to 6 per cent of water; it is probably colloidal MnO_2 containing these substances in the adsorbed condition.

SECTION XI

THE DIOXIDES—(*Continued*)

QUARTZ AND THE OTHER VARIETIES OF SILICA

Quartz.—Oxide of silicon; SiO_2; Si = 46·7, O = 53·3.

Hexagonal; symmetry, trigonal holoaxial. Common form, hexagonal prism, terminated by R {100}, *z* {22$\bar{1}$}.

$$a = 93° 56', \quad [a : c = 1 : 1·100].$$

$$R = \{100\},\ z = \{22\bar{1}\},\ m = \{2\bar{1}\bar{1}\},\ s = \{41\bar{2}\},\ x = \{4\bar{1}\bar{2}\}.$$

$$m\text{R}\ (2\bar{1}\bar{1}) : (100) = 38° 13',\ \text{R}z\ (100) : (22\bar{1}) = 46° 16',\ \text{R}s\ (100) : (41\bar{2}) = 28° 54',$$
$$zs\ (22\bar{1}) : (41\bar{2}) = 28° 54',\ sx\ (41\bar{2}) : (4\bar{1}\bar{2}) = 25° 57'.$$

Twinned on axis [111], or on face {10$\bar{1}$}. Cleavage R {100}, very imperfect. Brittle. Fracture, conchoidal. H = 7; G = 2·65. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction, weak: $\omega = 1·544$. Birefringence, positive, weak; $\epsilon - \omega = 0·009$. Rotatory polarisation strong: for 1 mm. thickness, line A, 13°; line D, 22°; line G, 43°. Infusible before the blowpipe. Insoluble in acids.

With the above description compare crystals from **Herkimer County** (New York).

Quartz is not only the most common, but, from every point of view, one of the most interesting of minerals. The beauty of the transparent glassy crystals and their regular geometrical form attracted attention from the very earliest times; it was known to the ancients by the name κρύσταλλος (ice), and was supposed by them actually to be ice. As was mentioned on p. 11, it furnished Steno with the material for his observations on the constancy of angles in crystals, and subsequently no mineral has been the subject of more crystallographic study. It has also been employed in countless investigations upon optical, electrical, magnetic, and other physical problems. Some of its varieties, such as amethyst, cairngorm, and rose-quartz, have always been prized as ornamental stones. It is cut into gems, ornaments, balance weights, spectacle glasses, prisms, and lenses; in grains and powder it is a valuable cutting and polishing material; and it is used in the manufacture of glass and porcelain.

Quartz may be fused and drawn into the finest threads and used in the place of silk fibres for delicate physical experiments.

The same glassy form of silica, made by fusing quartz, is also used for

the construction of chemical apparatus. Owing to its low coefficient of expansion it is not liable to crack on sudden change of temperature.

Quartz is also the most ubiquitous of minerals and has been formed under the most diverse conditions both by igneous and aqueous agencies; it is a universal constituent of granite and other acid rocks of igneous origin; it permeates all manner of geological formations as an aqueous infiltration, and is the common veinstuff of lodes and veins; in the form of grains it constitutes almost the whole mass of the sands and sandstones so widely distributed upon the earth's surface.

The name quartz is a German word of unknown origin, and has come into universal use in all languages since the sixteenth century.

The regular shape and the smoothness of this mineral are described by Pliny: *Quare sexangulis nascatur lateribus non facile ratio inveniri potest; eo magis quod neque mucronibus eadem species est, et ita absolutus est laterum laevor, ut nulla id arte possit aequari.*

No more instructive example exists of the principles of crystalline

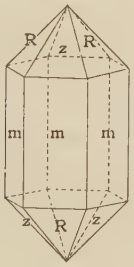


Fig. 552.—Quartz, *m* {2$\bar{1}\bar{1}$}, R {100}, *z* {2$\bar{1}$2}.

Fig. 553.—Quartz, R {100}, *z* {2$\bar{1}$2}.

symmetry, both geometrical and physical. The ordinary crystals, when doubly terminated, resemble a combination of hexagonal prism and bipyramid (Fig. 552); sometimes (as at Cleator Moor, in Cumberland) the form resembles a simple bipyramid (Fig. 553). The trigonal character of the symmetry is, however, displayed by many crystals, such as those which are common in the metalliferous veins of Schemnitz in Hungary, in which at each end three alternate faces of the pyramid are larger than the remaining three (Figs. 556, 562, 572), showing that the hexagonal bipyramid consists of two rhombohedra, R {100}, and its inverse, *z* {22$\bar{1}$}; sometimes, *e.g.* from Hungary and Brazil, the crystals are terminated by the one rhombohedron R only, and at some localities (*e.g.* from Bristol, small brown crystals enclosing clay) the mineral has been found as simple rhombohedra, R, which resemble cubes, the rhombohedron-angle (100) : (010) being 85° 46′. Moreover, though the cleavage is hard to obtain by fracture, a quartz crystal, when heated and plunged suddenly into cold water, breaks up with an imperfect cleavage along the same rhombohedron of 85° 46′. Further, the faces of *s* {41$\bar{2}$} occur only on alternate angles of the prism, and this form is a trigonal, not a hexagonal, bipyramid.

The trigonal character being thus established, the holoaxial symmetry

is clearly shown by such crystals as Fig. 554, in which the faces x are obliquely situated on *alternate* corners and constitute the trigonal trapezohedron of Fig. 195. The same combination is represented in Fig. 555 turned about the principal axis through an angle of 60° or 180°, in order to bring it into the position adopted in their figures by most authors; and the position of Fig. 555 will be generally retained in the figures of

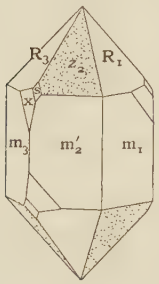


Fig. 554. — Quartz, right-handed crystal, m {2$\bar{1}\bar{1}$}, R {100}, z {2$\bar{1}$2}, s {1$\bar{2}$4} x {$\bar{1}$2$\bar{4}$}.

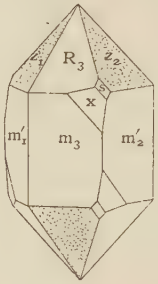


Fig. 555. — Quartz, right-handed crystal, turned through 60° from the position of Fig. 554.

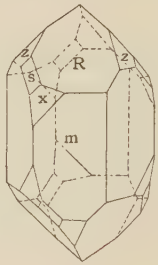


Fig. 556. — Quartz, left-handed crystal of trigonal habit.

quartz. Possessing no plane or centre of symmetry, the crystals are enantiomorphous. Fig. 557 represents what is conventionally called a right-handed crystal, and Fig. 558 the corresponding left-handed crystal: the two varieties are about equally common. They may be distinguished in three ways: (1) by the position of the x-face, which in a right-handed

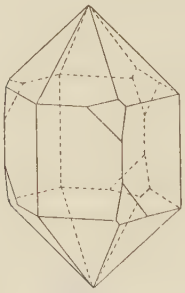


Fig. 557.—Quartz, right-handed crystal.

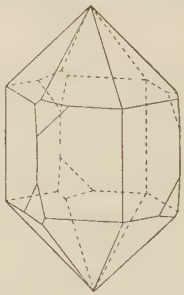


Fig. 558.—Quartz, left-handed crystal.

crystal lies below the right-hand corner of R; (2) by the direction of the zone $mxsz$, which in a right-handed crystal follows the direction of the thread of a right-handed screw at both ends of the crystal (Fig. 555); and (3) by the direction of the striæ on s, which are parallel to the edge sR, and therefore follow the direction of the zone $mxsz$ (as in the left-handed crystal, Fig. 562). By means of these striæ it is easy to determine the right- or left-handed character of any crystal on which s exists, even when x is absent and when R and z cannot otherwise be distinguished. The

face s is often, from its shape, called the " rhomb-face," lying in the zones Rm and zm ; it belongs to a trigonal bipyramid. Faces, like x, which belong to a trigonal trapezohedron are often called the " plagihedral " or " trapezohedral " faces. The striations on s serve to distinguish the forms R and z, since they are always parallel to the edge sR ; these forms often differ also in surface-characters, R being bright, and z dull ; R is also marked with little curved triangles, as in Figs. 562, 563, 566. The positions of these faces, as they occur on a left-handed crystal, are shown in the projection, Fig. 559. When other more acute rhombohedra are present, those which are below R have brilliant, though often rounded, faces (M, e in Fig. 568) ; those below z are horizontally striated or dull.

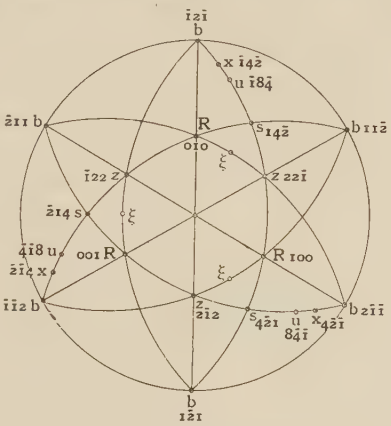


Fig. 559.—Quartz, projection of a left-handed crystal.
$b=m$ of preceding figures.

From what has been said it might appear that trapezohedral faces necessarily lie below R ; they are sometimes found below z. " Positive " trapezohedral faces, situated below R, are more frequent than " negative " trapezohedral faces which are situated below z. Right-handed crystals display positive trapezohedra under the right corner of R, negative trapezohedra under the left corner of z. In left-handed crystals the positive trapezohedra are under the left corner of R, negative under the right corner of z. The two sorts of crystals are, in fact, in all respects the reflections of each other, and the trapezohedral faces are grouped about s in each. Complementary right and left faces would have the positions of $x\underline{x}$ in Fig. 564 ; but when such faces occur upon the same crystal, this is invariably found to be, not a single crystal, but an interpenetrant twin.

The twinning of quartz can be deciphered by means of the faces sx, and is found to be extraordinarily varied.

(1) *Twin-axis* [111], parallel to the prism-edge ; interpenetrant twin.—The right-handed crystal of Fig. 555 being turned through 180° about the vertical axis [111] is brought into the position of Fig. 554. Two such crystals, interpenetrating completely, yield a crystal like Fig. 560, in which the twinning is disclosed by the appearance of x (and s) upon *adjacent* corners. In Fig. 560 the edges and corners which are developed are those that carry the faces x of one individual and $\underline{x}$ of the other; if they had been those edges of Figs. 554 and 555 from which x is absent, the crystal would resemble Fig. 552. Even in this case, however, the twin-structure may often be recognised by the fact that R of one crystal coincides with z of the other ; a pyramid-face may consist, for this reason, of parts which are bright, belonging to R of one individual, alternating with parts which are dull, belonging to z of the other individual. A curious pattern may then

be seen upon the pyramidal terminations, marking the boundaries of the two interlacing crystals, as shown in Fig. 561. These may interpenetrate quite irregularly, or the crystal may even be an individual which contains only one small corner of a second individual twinned with it. The presence of the face *s* or *x* upon any two adjacent corners is sufficient to betray the twinning. Two *left-handed* crystals may be twinned together,

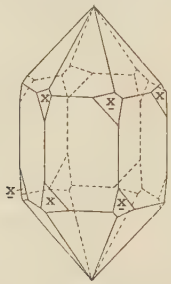


Fig. 560.—Quartz, right-handed, twinned on axis [111].

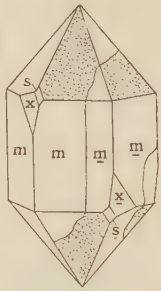


Fig. 561.—Quartz, right-handed, twinned on axis [111].

according to this law, and give rise to similar twins (Fig. 563); in these the striations on *s* are of the sort shown on Fig. 562. In Fig. 563 the R-faces can be recognised by their triangular markings, and the *z*-faces by their dullness.

(2) *Axis of alternating twinning* [111], parallel to the prism-edge; interpenetrant twin.—Let the crystal of Fig. 557 be united, not with the right-

Fig. 562.—Quartz, left-handed crystal.

Fig. 563.—Quartz, left-handed, twinned on axis [111].

handed crystal of Fig. 554, but with the left-handed crystal of Fig. 558, which may be derived from it by a half-turn about the vertical axis followed by reflection over the horizontal plane. An intergrowth is then obtained of a right-handed with a left-handed crystal (Fig. 564), such that the R-faces of the two individuals coincide. The crystal as a whole is now symmetrical to vertical planes passing through the centres of its faces and parallel to the faces of the prism $\{10\bar{1}\}$, which would truncate the edges of the prism *m*. This law is therefore usually described as twinning about $\{10\bar{1}\}$. As in the first law, the interpenetration may be quite irregular, but twinning

will usually be betrayed by the development of right-handed faces x, or of s-faces with right-handed striations, on some corners, and of left-handed faces on others. On account of its frequent occurrence in crystals from Brazil this is sometimes called the *Brazil law*. Here there is no tessellation of the R- and z-faces, as in Fig. 561. A juxtaposition-twin according to this law is shown in Fig. 246.

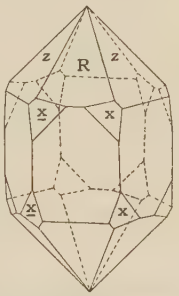


Fig. 564. — Quartz, alternating twin on axis [111].

(3) *Twin-plane* (111) perpendicular to the prism-edge; interpenetrant twin.—Crystals which resemble the last in containing both right and left quartz are sometimes, though rarely, found in which the two x-faces occur, not upon adjacent corners, as in Fig. 564, but upon the same corner, as in Fig. 565. This figure represents an intergrowth of the crystal of Fig. 557 with that of Fig. 558, after the latter has been turned through 180° about the principal axis; the same result is obtained by reflecting Fig. 557 over a horizontal plane, and the law may therefore be described as twinning about the plane (111).

Very many crystals of quartz, when carefully examined, bear evidence of twinning according to one or other of the above laws; if the crystal consists entirely of right-handed or of left-handed material the twinning

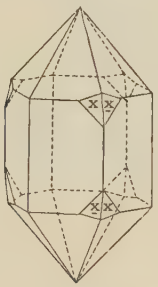


Fig. 565.—Quartz twinned on plane (111).

Fig. 566.—Quartz twinned on (5$\bar{1}$2), from Japan.

is about an axis alone (Law 1); if it contains both right and left quartz the twinning can only be expressed as involving reflection about a plane, and is generally a case of Law 2.

(4) *Twin-plane* ξ (5$\bar{1}$2); juxtaposition-twin.—One very rare form, ξ {5$\bar{1}$2}, which is shown in the projection, Fig. 559, as truncating the pyramid-edge Rz, is there inserted because it is of importance as a twin-plane. The twins considered above are interpenetrant and have their principal axes coincident; twinning about ξ causes two crystals to unite with their principal axes nearly at right angles to each other.

Here, Fig. 566, the two individuals have one pair of edges Rz parallel, and their principal axes are inclined at 84° 33′. A large number of these have been found in Japan; previously only a very few examples were

known from an old mine near Bourg d'Oisans in Dauphiné. At both localities the crystals are invariably flattened in the plane which contains the principal axes, and they intersect in a zigzag line. There has been some discussion as to whether the twinning is by reflection over the plane ξ, in which case one individual must be right- and the other left-quartz, or by hemitropy, either about the edge Rz or in the plane of the face ξ, in which case the two individuals are of the same sort. Generally each individual is found to be itself a Brazil twin, so that the distinction cannot be established. Fig. 567 is from a photograph of a magnificent specimen from Bourg d'Oisans, now in the British Museum.

Figs. 562 and 563 illustrate the sort of faces found upon quartz, with their natural markings. At some localities remarkable forms with very

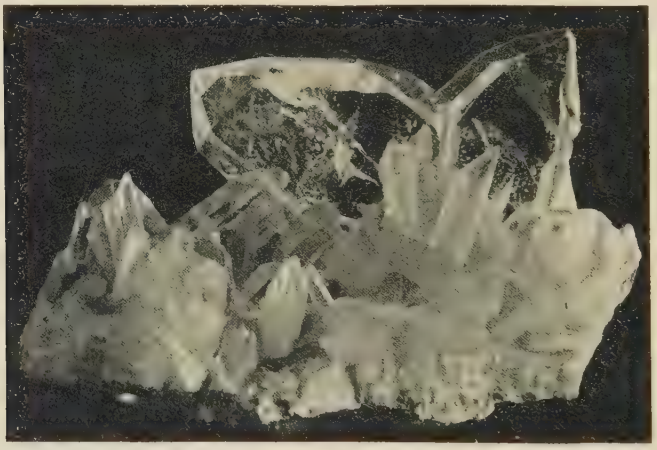


Fig. 567.—Quartz twinned on (5$\bar{1}$2), from Dauphiné (British Museum).

high indices prevail, *e.g.* in Alexander County, North Carolina (Fig. 568). Some of these faces, though perfectly bright and smooth, may be prerosion planes, for the crystals exhibit considerable signs of etching. It is at such localities that, as a great rarity, the basal plane (111) is occasionally found as a rough surface ; it is otherwise unknown in this mineral, and is probably only developed as a prerosion face.

Fig. 568, a twin on Law 1, illustrates the difference between the direct and inverse rhombohedra, which lie below R and z respectively. In this figure $z = \{2\bar{1}2\}$, $s = \{4\bar{2}1\}$, $u = \{8\bar{4}\bar{1}\}$, $y = \{10.\bar{5}.\bar{2}\}$, $x = \{4\bar{2}\bar{1}\}$, M $= \{7\bar{2}\bar{2}\}$, $e = \{11.\bar{4}.\bar{4}\}$, W $= \{16.\bar{1}\bar{4}.7\}$, and the dull faces adjacent to M and e are the forms inverse to them, *viz.* $\{\bar{5}44\}$ and $\{\bar{3}22\}$.

Misshapen crystals of quartz (*cf.* p. 11) are common and sometimes puzzling, but they may always be deciphered by means of the horizontal striations on the rarely-failing prism-faces m (Figs. 562, 563).

Right- and left- handed quartz is also right- and left-handed in the optical sense ; if a source of plane-polarised light be viewed along the

principal axis of a crystal like Fig. 557, the plane of polarisation is rotated to the right ; in a crystal like Fig. 558 to the left. Among minerals quartz may be identified by the characteristic interference-figure (p. 184, Fig. 365). When right-quartz and left-quartz overlap, Airy's spirals are seen. A basal section of a crystal twinned according to Law 2 or Law 3 generally shows in some parts a tint which is proved by rotation of the polariser to belong to right-quartz, in some parts the same tint belonging to left-quartz, and in other parts Airy's spirals. The arrangement of the right and left material is sometimes in regular triangular sectors whose bases are the sides of the hexagonal section. Of course, if the section be very thin, as in microscopic preparations of rocks, these effects may not be visible, and the figure will appear to be a normal one.

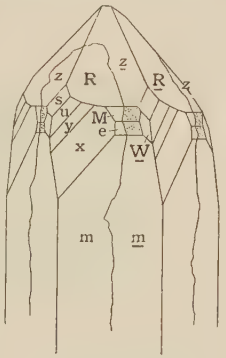


Fig. 568.—Quartz from North Carolina.

The electrical properties indicate the holoaxial symmetry in the most striking manner ; the principal axis is not polar, but the three horizontal axes of digonal symmetry (which would emerge through the prism-edges in Figs. 554 and 555) are polar, since one end of each such axis emerges through a prism-edge which carries the faces *sx*, the other end through those prism-edges from which these faces are absent. These lines are also axes of pyroelectric polarity. When a crystal is

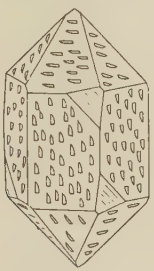


Fig. 569.—Quartz, right-handed, etched with HF.

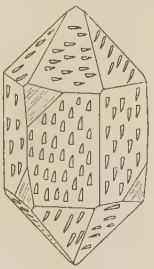


Fig. 570.—Quartz, left-handed, etched with HF.

treated by Kundt's method (p. 129) the edges bearing *s* and *x* become, during cooling, negatively electrified, and the others positively ; similarly, a basal section—a mere hexagonal plate—will attract the red lead to three alternate corners of the hexagon and the yellow sulphur to the other three corners.

Etching, both natural and artificial, is equally characteristic. Fig. 569 represents a right-handed, and Fig. 570 a left-handed crystal, etched with hydrofluoric acid ; the one figure is a complete reflection of the other. The twinning on Laws 1, 2, and 3 is indicated, both in pyroelectric experiments and in the etching, by like parts of the crystal occupying adjacent, instead of alternate, positions (*cf.* Figs. 560, 564, 565).

There is scarcely any important feature of crystals which is not well illustrated by quartz. The manner in which a crystal grows in parallel layers is exemplified by the so-called "capped quartz," in which one shell can be separated from another (Fig. 571); the inner kernel has here been

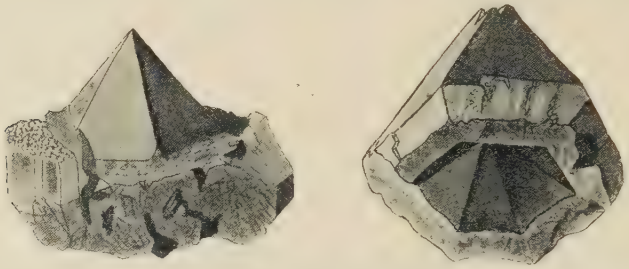


Fig. 571.—Capped Quartz.

coated with a fine deposit of clay, mica, or other material which has prevented the subsequent layer from adhering to it. "Ghost-quartz" (Fig. 572) is a transparent crystal, in which such a deposit makes the kernel visible within, although the later shell cannot be separated from it.

A remarkable example of curvature of crystal-faces is supplied by "twisted quartz." Sometimes this appears to consist of a single warped crystal, but on close inspection is found to be made up of many individuals, each being twisted about one of the digonal axes through a small angle from the position of its neighbour; their arrangement is really of a spiral character. This must be intimately connected with the symmetry, for the spiral twist is right-handed in the case of right-quartz, and left-handed in the case of left-quartz. Tschermak regards these as twin-growths in which the twin-axes are inclined at a small angle to the prism-edges, so that successive individuals are nearly, but not quite, parallel. Similarly, in the interpenetration-twins described above (Laws 1, 2, and 3), the individuals are sometimes not quite parallel, and the twinning may be then also of a "vicinal" character. There is thus sometimes an inequality of surface on the pyramid-faces of the twinned crystals, and especially a twin-suture down the prism-faces, as shown in Figs. 561, 563, 568.

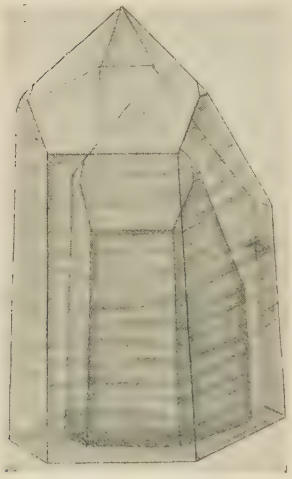


Fig. 572.—Ghost-quartz from Brazil.

Intergrowths of right- and left-quartz generally break with a ribbed surface, known as the "ripple-fracture," which appears to be connected with a kind of lamellar twinning, which may possibly have been caused by pressure.

As a constituent of such igneous rocks as granite quartz usually shows no definite crystalline form, since it has been the last mineral to crystallise and merely fills the spaces between the other constituents. But in quartz-porphyries and certain other igneous rocks it occurs in porphyritic crystals having the form of Fig. 553. The usual outline of such crystals in thin section will be either hexagonal (basal section) or rhombic (vertical section). No regular cleavage-cracks will be visible, and the crystals or grains are transparent and colourless, often containing numerous minute cavities or dot-like inclusions, some of which may be seen under high magnification to be partly filled with liquid. The refractive index is nearly the same as that of balsam, and the surface is therefore almost invisible. Between crossed nicols sections of medium thickness yield colours not higher than the white or yellow of the first order.

Rock crystal (Germ. *Bergkrystall*) is the colourless glassy quartz, of which the best examples are to be found lining cavities in the crystalline

Fig. 573.—Quartz, group from Cornwall (British Museum).

schists, as in the St. Gothard and at Bourg d'Oisans, in marble, as at the Carrara quarries, or in sandstone, as at Herkimer County, New York. Enormous crystals have been found in Brazil, Madagascar, and Japan (from which the well-known crystal spheres are turned). Doubly terminated crystals are mostly found in soft materials, such as clays and marls. Glittering crystals of quartz are generally known locally as "diamonds," *e.g.* Bristol, Wicklow, or Lake George diamonds.

Rock crystal often contains enclosures; the *flèches d'amour*, enclosed hairs of rutile, have been mentioned on p. 415; fibrous actinolite or asbestos is common in Cornish crystals. Cavities (which often have the exact form of the quartz itself, so-called "negative crystals") sometimes contain liquid, either water or liquid CO_2, and these not infrequently enclose a movable bubble. The quartz from Herkimer County encloses anthracite. "Avanturine quartz" has a shimmer due to spangles of mica or hæmatite enclosed in it.

Many coloured varieties of quartz are known:

Amethyst is violet quartz, of which the colour has been attributed to manganese, but it usually changes to yellow on heating. Amethyst is invariably composed of right- and left-quartz, breaks with the ripple-fracture, and shows Airy's spirals. By some authors the name is consequently used to denote all quartz having this structure, whatever its colour.

The beautiful masses used for ornamental purposes are found lining geodes and veins in Brazil, or as pebbles in Ceylon. The amethyst from Mursinka, in the Urals, generally contains liquid CO_2, with movable bubbles of the gas.

Smoky quartz includes the yellowish, brownish, and black crystals, of which beautiful specimens have been found in the Alps. Some of the quartz lining cavities in granite is the black variety known as "morion"; in the granite, for example, of Mursinka, and of the Mourne Mountains in Ireland. When cut as a gem the brown and yellow varieties are generally known as "cairngorm," from the locality in Banffshire, Scotland, where fine examples are found.

Yellow quartz, of a topaz colour, is known as "citrine."

Milky quartz is white and nearly opaque, and is very common among the crystals and masses which line the sides of veins.

Rose-quartz, a pale red material used for ornaments, may owe its colour to titanium or to manganese; the fine masses found in granite at Rabenstein in Bavaria are certainly associated with manganese ore. Good pieces are also brought from Finland. Rose-quartz is for the most part massive.

True *cat's-eye* is a variety of chrysoberyl, but an opalescent quartz which, when cut *en cabochon*, reflects the peculiar band of light shown by the former mineral, is known by the same name. The effect is caused by a fibrous structure, and may be due to silky fibres of asbestos or to quartz replacing them. The beautiful, golden "crocidolite" from Griqualand in South Africa consists largely of quartz replacing a fibrous amphibole.

Owing to the wide diffusion of siliceous solutions, quartz is found replacing (or pseudomorphous after) many minerals; but on account of its own resistance to solvents it is itself scarcely ever altered into other minerals. Most remarkable, therefore, are the pseudomorphs of steatite after quartz found at Göpfersgrün in Bavaria; these are perfect crystals completely transformed into steatite, and are found in a band of that mineral at the junction of granite with crystalline schists; their production is difficult to explain.

The bipyramidal porphyritic crystals of quartz mentioned above (p. 429)

as occurring in certain igneous rocks represent a polymorphous modification of silica (sometimes distinguished as β-quartz) [1] which is stable at temperatures above 575° C. This has angles very nearly the same as those of ordinary (or α-) quartz, but its symmetry is hexagonal, not trigonal, and the bipyramids are bounded by twelve similar faces instead of being a combination of two rhombohedra. It shows rotatory polarisation and belongs to the hexagonal holoaxial class. On cooling down, the β-quartz is converted into α-quartz; and the porphyritic crystals in question are thus pseudomorphs (" paramorphs ") of α-quartz after β-quartz. The case is similar to that of leucite (p. 508). On the decomposition of the enclosing rock by weathering the quartz crystals are set free, and loose isolated crystals may be found in the soil. Such crystals are not infrequently twinned, two bipyramids being juxtaposed with their principal axes

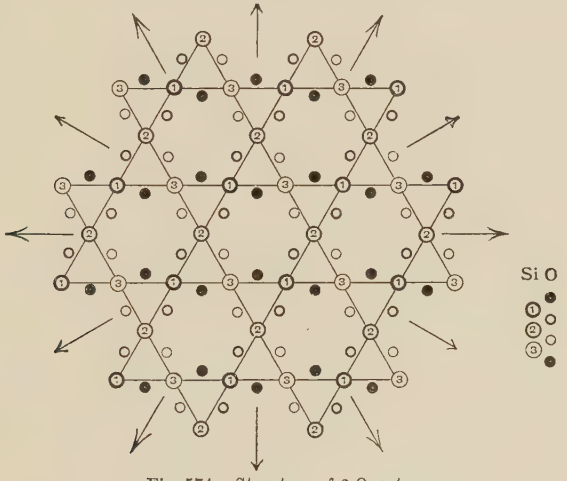


Fig. 574.—Structure of β-Quartz.

inclined at an angle of 76° 26′ (twin-plane $(01\bar{1}1)$, corresponding to R or z of α-quartz), or of 84° 33′ (twin-plane $(2\bar{1}\bar{1}2)$, corresponding to ξ).

The complete determination of the structure of quartz has been found to present serious difficulties. It appears, however, that in β-quartz the silicon atoms form three prismatic lattices of 120°, Fig. 410 (vi), which interpenetrate in a spiral manner as shown in Fig. 574, which represents the structure when viewed along the vertical axis. The silicon atoms are here represented by the larger circles, the three constituent lattices being distinguished by the figures, 1, 2, 3. If the atoms of the lattice 2 are supposed to lie in the plane of the paper, those of 1 will lie above this, and those of 3 below it, at a distance of one-third the height of the lattice cell. They thus form two sets of spirals, surrounding the triangular and the hexagonal spaces, respectively. The symmetry is that of the hexagonal holoaxial class, with six lateral two-fold axes.

[1] Some authors distinguish this modification as α-quartz, and use β-quartz for the ordinary mineral.

The oxygen atoms are also arranged spirally, and are probably grouped in a tetrahedral manner about each silicon atom, as indicated in the

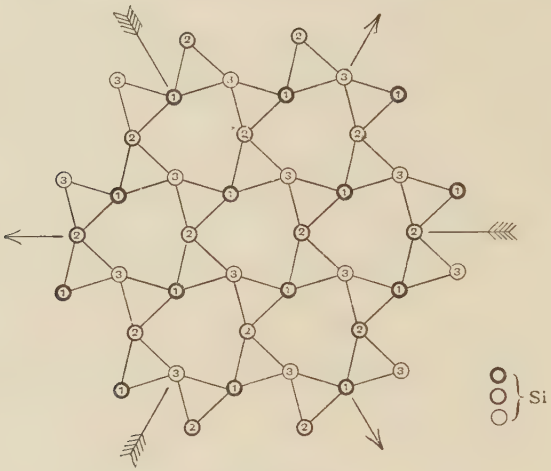


Fig. 575.—Structure of α-Quartz.

figure, the horizontal planes in which they lie being half-way between the successive silicon planes.[1]

The close resemblance, in form and physical properties, which exists between α- and β-quartz seems to indicate that the difference between the two structures is only slight; and, according to Sir W. Bragg, on the conversion of β-quartz into α-quartz the structure suffers a slight distortion, by a relative displacement of the three lattices, as shown in Fig. 575. The spiral arrangement remains, but the symmetry is now trigonal only, and corresponds with that of the trigonal holoaxial class, characteristic of ordinary quartz, with three lateral axes which are polar in character, as shown by the arrows.

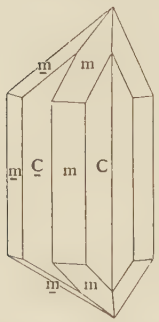


Fig. 576.—Tridymite, C {0001}, *m* {10$\bar{1}$0}.

Tridymite.—This mineral, found in colourless hexagonal scales and plates lining cavities of an andesite from Mexico, and subsequently found in the trachyte of the Siebengebirge and other localities, though having the same composition, SiO_2, is quite distinct from quartz. It has a basal cleavage; H = 7, G = 2·29; refractive index, 1·477. The name alludes to its common tendency to form the triplets of Fig. 576. The apparent hexagonal plates are themselves in reality pseudo-symmetric twins of biaxial, probably orthorhombic, material, which only becomes uniaxial above 120° C. Tridymite is probably identical with a remarkable

[1] Sir W. Bragg and R. E. Gibbs, *Proc. Roy. Soc.*, A, 1925, vol. cix, p. 405.

orthorhombic (?) form of silica named "asmanite," which was found by Maskelyne in the meteorite of Breitenbach, quartz itself being quite unknown in meteorites. Tridymite, unlike quartz, is soluble in sodium carbonate solution; it may possibly be isomorphous with brookite.

Cristobalite.—Another, still rarer, form of silica, which has been found in Mexico in small pseudo-cubic (tetragonal) crystals resembling octahedra, is known as **cristobalite**. It shows a very weak double refraction, which disappears on heating to 180° C., and above this temperature the crystals become really cubic.

Quartz, tridymite, and cristobalite form a remarkable polymorphous group of minerals, each of which is stable within a certain range of temperature. This temperature is highest for cristobalite and lowest for quartz. The three minerals are widely different in their crystalline form and other properties, and they only undergo mutual transformation with extreme slowness; but, as already mentioned, each of them can exist in two modifications which are closely related in their crystalline form and are mutually transformable with ease at definite temperatures.

Chalcedony.—Much of the silica which occurs in Nature, even much of that which accompanies rock-crystal, is an apparently amorphous substance, translucent, having a waxy lustre, with a specific gravity of about 2·6, a hardness equal to that of quartz, and an even fracture. This material, chalcedony, appears to have been always deposited from aqueous solution; it fills cavities in decomposed igneous rocks, or lines geodes and veins; it generally has a banded structure (Fig. 577), and varies much in colour from white, yellowish-brown, dark brown, to blue (see under agate, p. 436). When free to assume a form of its own it is frequently concretionary, mamillary, botryoidal, or stalactitic. The most remarkable specimens are the fantastic, arborescent stalactites formerly found in the Trevascus Copper Mine near Camborne in Cornwall. Wherever silica has been carried away in solution from decomposed silicates chalcedony is apt to be deposited; it is frequently the material of pseudomorphs. Among striking examples may be mentioned the pseudomorphs of white chalcedony after octahedra of fluor from Beeralston in Devonshire, and those of pale or smalt-blue chalcedony after cubes of fluor from Tresztya in Transylvania; large crystals of what looks like stained quartz, formerly found in the iron mine of Haytor in Devonshire, were called "haytorite," and were supposed to be a new mineral; they have been proved to be pseudomorphs of chalcedony after datolite.

Under the microscope chalcedony is found to be crystalline, consisting of minute fibres, which are biaxial and positive, with straight extinction, and elongated along the obtuse bisectrix, *i.e.* in a negative direction; they are therefore quite distinct from true quartz, and chalcedony is not, as was formerly supposed, merely a massive or micro-crystalline quartz.

Considerable attention has been paid to the microscopic characters of massive silica, and other varieties have been distinguished. "Quartzine" is the name given to one in which the fibres are biaxial and positive, but

elongated along the *acute* bisectrix ; this may be merely a different habit of chalcedony. The blue pseudomorphous material from Tresztya just mentioned appears to consist partly of a mineral having a specific gravity 2·04, and refractive index 1·446 ; identical, therefore, in these respects with opal, but fibrous, and, like quartzine, elongated in the positive direction. It has been called " lussatite " from a locality in Puy-de-Dôme, where it also occurs.

Opal.—Hydrated silica ; $SiO_2 + xH_2O$.

Amorphous (colloidal). Brittle. Fracture, conchoidal. H = 6 ; G = 2·1. White. Streak, white. Lustre, vitreous, or resinous. Translucent ; μ 1·455. Infusible, but yields water. Soluble in potash.

With the above description compare common white opal from **Cornwall.**

Opal shows no trace of crystallisation, and is only found in bands and layers, in botryoidal or stalactitic masses, filling cavities, pseudomorphous after other minerals, or replacing organisms ; it has been deposited in many places to which siliceous waters have had access, especially in decomposed igneous rocks, and frequently accompanies quartz and chalcedony. It is a colloidal " gel," and the proportion of water which it contains varies considerably ; the ordinary amount is from 5 to 10 per cent ; some varieties contain as much as 30 per cent ; some are practically anhydrous. It can generally be recognised by its greasy lustre, and identified by the low density and refractive index as compared with the other varieties of silica. In these respects the lussatite mentioned above is the only silica which possesses the same properties as opal. Opal, when cut and polished with a plane surface, may very conveniently be distinguished from quartz by means of the total reflectometer.

The description given above applies to the common white opal, but two other varieties merit particular attention.

Hyalite (ὕαλος, glass) is a perfectly transparent, colourless, and glassy opal, usually found as a botryoidal or mamillary incrustation ; it contains a small proportion of water. The little hemispheres detached from botryoidal groups are birefringent, and give a black cross under the microscope in parallel light ; but this effect is probably due to the strain introduced when the substance solidified from solution. Good specimens of hyalite occur in cavities and amygdales of basalt at Waltsch in Bohemia.

Precious opal is the name given to the varieties which exhibit a beautiful play of colours ; this property, in spite of the inferior hardness, low refractive power, and opacity of the stone, makes it one of the most valuable of gems. No other mineral presents such a varied and brilliant play of colours. The transparent opals are of no particular beauty ; it is the opaque and translucent varieties which yield by reflected light the remarkable mother-of-pearl colours which have made the opal famous. The colours are interference effects due in the precious opal to the presence of thin films. Whether these films are mere cavities (cracks filled with air),

or fine interpositions of opal whose refractive index differs slightly from that of the main mass, is not quite certain. The latter explanation is probably the correct one ; but in any case the films or cracks seem to have resulted from the loss of water during solidification of a jelly-like material, and the difference of refractive index may depend upon the difference in the proportion of water.

Sometimes the effect is that of vari-coloured spangles ; sometimes all the opal from a certain locality presents a single prevalent colour. Three localities afford very typical specimens. Until modern times most precious opal came from the neighbourhood of Czerwenitza in Hungary, where it is found disseminated through an altered trachyte, and consists of small spangles of very varied shades of yellow, green, blue, and red. Specimens often consist largely of the grey matrix. Queensland has produced a precious opal which occurs as nodules and pipe-shaped pieces in a brown, jaspery limonite ; the best have come from Barcoo River ; they generally have a prevalent blue and green colour. From Zimapan in Mexico a somewhat different variety, the so-called " fire-opal," is obtained ; this is a fiery-red opal without much play of colour, which fills cavities in a porphyritic trachyte.

Other names employed for varieties of opal are " wood-opal," which is wood converted into opal and still preserving its characteristic fibrous structure ; " menilite," or liver-opal, curious concretionary forms of an opaque, greyish-brown substance found in shale at Menilmontant near Paris ; " siliceous sinter," the globular, botryoidal, or platy incrustations deposited from hot siliceous waters ; this is sometimes fibrous, stalactitic, porous, or even powdery ; the varieties range from the colourless, glassy hyalite to the beautiful red, blue, and yellow crusts which fringe the geyser pools in the Yellowstone Park ; the siliceous sinter of the Iceland, New Zealand, and Yellowstone Park geysers is sometimes known as " geyserite " ; it is frequently almost powdery.

From what has been said above it will be seen that all chalcedony and opal, and much of the quartz, is deposited where aqueous solutions have permeated decomposing igneous rocks and carried away silica in solution. Two or three of these minerals frequently unite in the same mass, and numbers of special names have been given both to coloured varieties of each and to their mixtures.

" Jasper " is really a mixture of quartz with red or yellow hydrates of iron or with clay, so densely disseminated as to make the quartz quite opaque and creamy ; the most beautiful varieties are the deep red brought from Siberia, or found as pebbles on the plains of Argos in Greece ; and the rich yellow brought from India and Smyrna. The " riband-jasper " of the Urals consists of parallel, straight bands of reddish-brown and sage-green material.

The chief coloured varieties of chalcedony are " carnelian " (Germ. *Carneol*), translucent red with a waxy lustre ; " sard," brownish-red with a more horny appearance ; " plasma," a leek-green chalcedony ; " chrysoprase," an apple-green variety found in Silesia. The colour of chrysoprase

is probably due to nickel. The name " prase " belongs to green *quartz*, in which the colour is generally due to enclosed chlorite. " Blood-stone " or " heliotrope " is plasma spotted with blood-red jasper.

" Agate."—This name includes the banded and variegated chalcedonies ; these have generally been deposited in the interior of amygdales and cavities in decomposing igneous rocks. The bands follow the irregular contours of the cavity, and, when the agate nodule is cut across, present a beautiful succession of undulating or zigzag lines of different colours (Fig. 577). The material has probably been deposited from infiltrating solutions as a gelatinous mass, which has afterwards become hardened by loss of water. The banding may possibly have been produced later by the precipitation, in the jelly, of iron oxides or other substances from solutions diffusing inwards through it ; since a somewhat similar rhythmical banding can be produced artificially in gelatine impregnated with a solution of ammonium bichromate, by allowing a solution of silver nitrate to diffuse into it. Dark red silver chromate is thus formed, which is precipitated in successive bands, separated by clear spaces, as the diffusion proceeds. Sometimes the centre of the geode is occupied by crystallised quartz ; sometimes it is an empty cavity or is filled with water. The successive bands consist for the most part of differently coloured chalcedony, carnelian, jasper, amethyst, and rock crystal, and they may be so fine as to be indistinguishable except with the microscope. According to the form of their markings some agates are distinguished by the name of " ruin-agate," " fortification-agate," and " eye-agate " ; or according to their material as " carnelian-agate " and " jasper-agate."

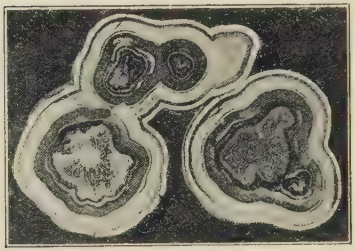


Fig. 577.—Agate from Uruguay (British Museum).

" Onyx " is agate in which the successive layers are parallel bands sufficiently flat to fit them for use as cameos in which the subject is cut in the material (usually white) of one layer upon that of the succeeding layer as background. Sometimes, and especially in the South American agates, a nodule consists of curvilaminar agate in the upper part, while the lower half, where the solution has been able to lie in horizontal layers, consists of horizontally banded onyx. Onyx which contains red bands of carnelian or sard is known as " sardonyx ".

" Moss-agate " (Fig. 451) is chalcedony filled with dendritic inclusions of chlorite, manganese oxide, or other minerals.

The name " flint " is applied to concretionary siliceous bands and nodules resembling chalcedony, which are found in the chalk. The silica has been derived from sponge spicules and other siliceous remains of organisms. Flint often contains crystallised quartz in its cavities. " Hornstone " and " chert " are names given to compact flinty varieties of chalcedony ; the latter is generally also of organic origin.

The best agates were formerly found as amygdales in melaphyre in the neighbourhood of Oberstein on the Nahe, where the great agate-cutting works have now existed for more than 400 years ; but the finest specimens now come from Rio Grande do Sul and Uruguay in South America, where they occur under similar conditions, together with quartz, citrine, amethyst, and carnelian. Fig. 577 represents a section of one of these amygdales ; the prevailing colour of these South American agates is usually pale greyish-purple. The bright colours (blue, brown, black, etc.) often seen in polished agates are produced artificially by staining. Fine agates are also found in the basalt, and as pebbles on the beach at Montrose in Forfarshire. Peculiar are the chocolate-brown jasper-agates found near Cairo in Egypt.

SECTION XII

THE ALUMINATES, ETC.

THE SPINEL GROUP

Spinel.—Aluminate of magnesium; $MgAl_2O_4$; $MgO = 28{\cdot}3$, $Al_2O_3 = 71{\cdot}7$. Cubic; holosymmetric. Common form, octahedron. Twinned on (111). Cleavage {111}, imperfect. Brittle. Fracture, conchoidal. H = 8; G = 3·5. Red. Streak, white. Lustre, vitreous. Transparent. Refraction, high; $\mu = 1{\cdot}715$. Infusible. Soluble with difficulty in sulphuric acid.

With the above description compare crystals from **Ceylon.**

Spinel in the red varieties found in the East (Burma, Ceylon) was prized as a kind of ruby from very early times; it has generally been known to jewellers by the name "balas ruby," and the two minerals were not distinguished until the time of Romé de l'Isle (1783).

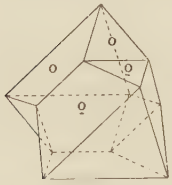


Fig. 578.—Spinel, twinned on (11$\bar{1}$).

Although the two minerals belong to different systems, a ruby which is a combination of {111} and {100} may easily be confused with a flattened octahedron of spinel. The latter is distinguished by the absence of well-defined cleavage, and of the triangular striations which mark the basal pinakoid of ruby, as well as by its inferior hardness and density. The small crystals of spinel found in the gem-bearing sands of Ceylon are usually simple octahedra which sometimes have their edges truncated by the dodecahedron. The typical "spinel twins" (Fig. 578), with twin-plane (111), are very common.

The rounded edges of spinel are not merely due to rolling in sands and gravels, for even when found in the limestone from which they are washed out they often have rounded edges; the crystal faces also often have a platy corroded appearance, and this characterises other minerals (pyroxene, idocrase, etc.) found in similar limestone. A blue spinel found in limestone at Åker in Sweden shows marked corrosion, and this variety is further peculiar as being of *cubic* habit.

Spinel is one of the few cubic minerals which exhibit no birefringence; its isotropic character and absence of pleochroism also serve to distinguish transparent crystals and facetted stones of spinel from ruby.

"Precious spinel," *i.e.* the crystals suitable for gems, exists in three colours—spinel-ruby, the red; almandine-spinel, the violet; and rubicelle, the orange-red. The analyses of red spinel show iron replacing magnesium, and traces of chromium, to which the colour is doubtless due.

Crystals of pure spinel obtained artificially by the action of aluminium chloride and steam upon red-hot magnesium, or the minute crystals found in basic iron slag, are absolutely colourless.

A Noteworthy Locality:

Vesuvius. — Lustrous black octahedra of iron-magnesia-spinel (pleonaste), with edges truncated by the dodecahedron, occur with pale-green augite, mica, and idocrase in the ejected blocks of Monte Somma.

Magnetite.—Ferrite of iron; $Fe''Fe'''_2O_4$; FeO = 31·0, Fe_2O_3 = 69·0.

Cubic; holosymmetric. Common form, octahedron and dodecahedron. Twinned on (111). Parting, {111}. Brittle. Fracture, uneven. H = 6; G = 5·2. Black. Streak, black. Lustre, metallic. Opaque. Magnetic and sometimes polar. Fusible with difficulty. Soluble in hydrochloric acid.

With the above description compare crystals from **Nordmark** (Sweden).

Magnetite (Germ. *Magneteisen*, Fr. *fer oxydulé*) is a mineral which has been known from very early times chiefly on account of its remarkable magnetic property. *Quid enim mirabilius? Aut qua in parte naturae maior improbitas? Quid lapidis rigore pigrius? Ecce sensus manusque tribuit illi* (Pliny). Pliny also tells a tale of its discovery by the shepherd Magnes, whose shoe-nails and staff were attracted by the rock on Mount Ida; but the name may really be derived from Magnesia, as a locality where it was found.

The modern importance of the mineral is as one of the most valuable ores of iron; it is worked on an enormous scale in Scandinavia.

Beautiful large isolated octahedra of magnetite are found in the chlorite- and talc-schists of the Alps.

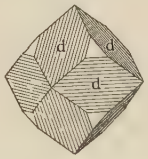


Fig. 579.—Magnetite, {110}, {111}.

At Nordmark in Sweden brilliant dodecahedra, or combinations of {110} and {111} of dodecahedral habit (Fig. 579), occur in the crystalline schists. Very characteristic are the striations on the dodecahedron-faces; these are parallel to the longer diagonals, and are due to a platy structure parallel to the octahedron. Spinel twinning (Fig. 578) is common, and leads to twin-lamellæ, which are probably the cause of the platy structure, and of the octahedral parting. Crystals rich in combinations of various forms have been described, but these are rare. Ordinary magnetite is massive or granular, as, for example, at the Scandinavian iron mines at Arendal, Dannemora, Gellivara, etc. The largest masses of "lodestone" have been found in the Urals and the Altai Mountains; pieces of magnetite sometimes exhibit a north and a south pole. Ordinary emery contains much magnetite.

As a heavy mineral, not prone to alteration, magnetite is one of the substances that become mechanically separated in alluvial deposits and

is sometimes found as a magnetic sand. Magnetite and hæmatite both occur as excessively thin dendritic deposits in the cleavage-laminæ of mica, where they may be sufficiently thin to be translucent.

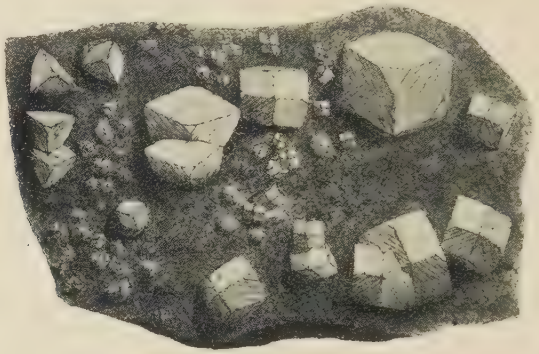


Fig. 580.—Magnetite from Nordmark (Sweden).

In whatever form the mineral occurs, it may always be identified by its magnetism ; the only other mineral which possesses the property in the same degree is ferriferous platinum. In a crystal of magnetite the position of the magnetic poles has no particular relation to the form of the crystal.

Some Noteworthy Localities :

Arendal (Norway).—Large beds of magnetite occur in the gneiss, crystalline schists, and limestone ; the magnetite is usually granular and accompanied by pyroxene, amphibole, garnet, and calcite. The cavities in the rock are sometimes lined with brilliant dodecahedral crystals of magnetite (*cf.* Fig. 580).

Zillerthal (Tyrol).—Large octahedra perfectly formed on all sides occur in a compact chlorite-slate ; many of these are spinel twins. Associated with this occurrence are minute crystals in a foliated limestone.

The members of this group all conform to the type $R''R'''_2O_4$, and may be regarded as cubic aluminates and ferrates of divalent metals, together with the corresponding chromium compounds. The chief minerals in the group are :

Spinel	$MgAl_2O_4$
Gahnite	$ZnAl_2O_4$
Magnetite	$FeFe_2O_4$
Franklinite	$(Zn, Mn)Fe_2O_4$
Chromite	$FeCr_2O_4$

All these are found well crystallised, and generally of an octahedral habit. To them must be added a rare mineral, **magnesioferrite**, $MgFe_2O_4$, found as a sublimation product, with hæmatite, in the fumaroles of Mount

Vesuvius, and a black mineral named **jacobsite**, $MnFe_2O_4$, found in small octahedra in calcite at the manganese mines of Jakobsberg in Sweden.

The mutual replacement of Mg, Fe, Zn, Mn among the divalent, and of Fe, Mn, Cr, Al among the trivalent metals is common, and is indicated not only by the isomorphous mixtures which this group contains, but also by a whole series of independent minerals. Thus amongst the aluminates, or spinels proper, may be distinguished :

Magnesia-spinel or **spinel ruby**	$MgAl_2O_4$
Magnesia-iron-spinel or **pleonaste**	$(Mg, Fe)Al_2O_4$
Chrome-spinel or **picotite**	$(Mg, Fe)(Al, Fe, Cr)_2O_4$
Iron-spinel or **hercynite**	$FeAl_2O_4$
Zinc-spinel or **gahnite**	$ZnAl_2O_4$

Gahnite contains iron, replacing both the zinc and the aluminium ; and other such mixtures are common. Even the colour of the spinel ruby is due to intermixture with a small proportion of the chromium compound, as shown by the following typical analysis of a Ceylon crystal :

Al_2O_3	Cr_2O_3	FeO	MgO	SiO_2
69·01	1·10	0·71	26·21	2·02

Most of the spinels are stable compounds, and occur in good crystals : pleonaste (or ceylonite) as dark green or black octahedra of higher specific gravity than spinel, chiefly as a constituent of garnetiferous gneisses and metamorphic rocks ; picotite generally as heavy black grains ($G = 4$) in olivine-rocks (lherzolite, etc.), and in serpentine, sometimes as minute inclusions in olivine ; hercynite as black magnetic specks in the Saxon granulites ; gahnite occurs in greenish or black octahedra with a somewhat greasy lustre in a talc-schist at Falun in Sweden, where it originally received the name of automolite (or " the deserter ") from the unusual surroundings in which a zinc mineral there finds itself ; also in the zinc mines of New Jersey.

Among the other members of the spinel group, **franklinite** is somewhat allied to gahnite in composition ; it is a typical mineral of the Franklin Furnace Mine (New Jersey), where it occurs in large black octahedra with rounded edges, with the red oxide, zincite, and with green willemite, the silicate of zinc, and in sufficient quantities to be worked as an ore of that metal. Much of the ore is in fact a granular mixture of these three minerals. Franklinite is slightly magnetic.

One of the most important members of the spinel group, commercially, is **chromite,** since it is the source of the chromium which is now largely used in the manufacture of " rustless steel " and other alloys, and of the compounds of that metal which are used as pigments. Chromite itself is used as a refractory material for lining furnaces. Chromite is widely distributed, and always in olivine-rocks or in serpentine, especially the latter ; it is one of the heaviest ($G = 4{\cdot}5$), and at the same time one of the softest ($H = 5\frac{1}{2}$) of the spinel group ; it may be recognised among other black minerals which possess submetallic lustre, and are devoid of cleavage,

by the conspicuous reactions for chromium in beads of borax or microcosmic salt; but these may be largely masked by the iron reactions while the bead is hot. Chromite is sometimes very slightly magnetic.

The dunite, or olivine-rock, of the Dun Mountain in New Zealand, consists entirely of olivine and a black granular mineral containing:

Cr_2O_3	Al_2O_3	FeO	MgO
56·54	12·13	18·01	14·08

intermediate in composition between picotite and chromite; many minerals referred to chromite contain Mg and Al as well as Fe. The manganese, chromium, and iron in the various members of the spinel group are recognised by pyrognostic tests.

CHRYSOBERYL

Chrysoberyl.—Aluminate of beryllium; $BeAl_2O_4$; $BeO = 19·7$, $Al_2O_3 = 80·3$. Orthorhombic.

$$a : b : c = 0·470 : 1 : 0·580.$$

$p = \{111\}$, $A = \{100\}$, $i = \{011\}$, $m = \{110\}$.

$Ap\ (100) : (111) = 43°\ 8'$, $pp\ (111) : (1\bar{1}1) = 40°\ 7'$, $ii\ (011) : (0\bar{1}1) = 60°\ 14'$, $mm\ (110) : (1\bar{1}0) = 50°\ 21'$.

Twinned on (031). Cleavage {010} and {011}, imperfect. Brittle. Fracture, conchoidal. $H = 8\frac{1}{2}$; $G = 3·7$. Yellowish-green. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1·75$. Birefringence, positive; $\gamma - \alpha = 0·009$. Axial plane (010). Acute bisectrix perpendicular to (001); $2E = 84°\ 43'$; $\rho > v$. Pleochroic. Infusible. Insoluble in acids.

With the above description compare crystals from **Ceylon.**

Chrysoberyl is a rare mineral, and is chiefly known as a gem stone, rolled crystals from the alluvial deposits of Ceylon being used for this purpose; it is interesting on account of the twinning and the close relation which it bears to olivine. The mineral shows no resemblance to the spinel group, to which it is strictly analogous in chemical composition. Both the dark green crystals from the Urals, known as "alexandrite," and some of the yellowish-green stones from Ceylon, are beautiful examples of pseudo-hexagonal twinning similar to that of aragonite (Figs. 257, 258). Three interpenetrating crystals are united into a hexagonal plate with bevelled edges. The axes of chrysoberyl have been so chosen that the front of the plate (Fig. 581) is the face A, common to the three individuals, and this face is in each striated parallel to its intersection with (010); *i.e.* vertically in the central crystal of Fig. 581, which is in the normal position. The bevelling planes are p {111}, and the outline of the plate is formed by i {011}.

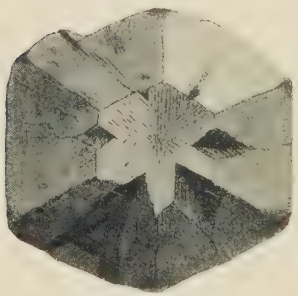


Fig. 581.—Chrysoberyl (Alexandrite) from Perm (Russia).

In the corresponding twin of aragonite two adjacent crystals are generally united along a surface which is nearly perpendicular to the twin plane ; if the chrysoberyl twin is of the same sort, the twinning is upon the planes i {011} ; but the chrysoberyl crystals may equally well be explained as due to twinning upon faces of {031}, nearly perpendicular to i, in which case the twin-plane is also the well-defined plane of union marked by the re-entrant angles on the edges and in the striæ at the centre of the plate ; the angle $(0\bar{3}1) : (011)$ is 90° 14′, so that only very accurate measurements could decide between these two possible explanations. If i (011) be twin-plane, then a pair of adjacent faces p (since they lie between i and A, both of which are common to two adjacent individuals) must fall into the same plane, as in the similar twins of cerussite (Fig. 615, p. 465) ; if $(0\bar{3}1)$ be plane of twinning and composition, two adjacent faces p will make a small re-entrant angle of 18′. The evidence is in favour of the latter, although {031} is not a form which is found among the crystal faces of chrysoberyl.

Both in shape and twinning the mineral closely resembles olivine ; both minerals have a pseudo-hexagonal zone $[ii]$:

Olivine, Mg_2SiO_4	$a : b : c = 0{\cdot}465 : 1 : 0{\cdot}586$	$ii = 60°\ 47'$
Chrysoberyl, Al_2BeO_4	$0{\cdot}470 : 1 : 0{\cdot}580$	$60°\ 14'$.

(tan $60° = \sqrt{3} = 1 : 0{\cdot}5775$).

This must be regarded as another instance of the "isomorphism" between chemically dissimilar but "isotypic" compounds, of which wurtzite - zincite and hæmatite-ilmenite have already been quoted as examples.

Some of the Ceylonese stones show a beautiful "chatoyance," and are much prized as gems ; the most remarkable are those known as "cat's-eye" ; owing to the wavy opalescence which it exhibits, this variety has also received the name of cymophane (κῦμα, a wave). The property may be due to fine tubular cavities parallel to the basal plane. This, the true cat's-eye, must not be confused with the quartz cat's-eye mentioned on p. 430. The pleochroism is well marked, the colours being red, yellow, and green for rays vibrating along the axes a b c respectively.

The deep green alexandrite appears red by transmitted light, and generally also by candle light. The light green chrysoberyl not only resembles olivine, but is often called chrysolite by the jewellers ; it may be distinguished from olivine by its superior hardness and density. Chrysolite (olivine) floats in a mixture of methylene iodide with iodine and iodoform (of specific gravity 3·6) ; quartz cat's-eye floats in methylene iodide ; chrysoberyl sinks in both.

SECTION XIII

THE BORATES

Boracite.—Borate and chloride of magnesium; $Mg_7Cl_2B_{16}O_{30}$; MgO = 31·6, Cl = 7·9, B_2O_3 = 62·3.

Pseudo-cubic, with apparently di-tesseral polar symmetry. Common form, cube with tetrahedron.

$$A = \{100\},\ d = \{110\},\ o = \{111\},\ \omega = \{1\bar{1}1\},\ n = \{2\bar{1}1\}.$$

Cleavage {111}, imperfect. Brittle. Fracture, conchoidal. H = 7; G = 3. Colourless. Streak, white. Lustre, vitreous. Translucent. Birefringent; biaxial; $\beta = 1{\cdot}667$; $\gamma - \alpha = 0{\cdot}011$; $2V = 90°$. Intumesces and fuses. Soluble in hydrochloric acid. Markedly pyro-electric.

The above description applies to crystals from **Stassfurt** (Prussia).

Boracite is a comparatively rare mineral found either in massive nodules or isolated crystals in the salt and gypsum deposits of Stassfurt. The massive mineral is a compact white substance, softer than the crystals, sometimes granular or earthy, and variously tinted by impurities which give it a green, yellow, or red colour.

Very perfect isolated crystals are found embedded in carnallite at Stassfurt, and in gypsum and anhydrite at Lüneburg near Hanover.

These crystals are from the theoretical point of view one of the most interesting of minerals. At first sight they are perfect cubic crystals displaying marked polar di-tesseral symmetry. The ordinary combination resembles that of cube with octahedron and dodecahedron, but it can generally be observed that the faces of one tetrahedron are large, those of the other small; one is bright, the other dull; or sometimes four corners of the cube are truncated by the tetrahedron {111} alone, while the remaining four corners carry the form {$2\bar{1}1$} (Fig. 582). At Lüneburg beautiful little crystals of a bluish tint are found which are simple tetrahedra, or tetrahedra with their edges truncated by the cube (Fig. 583).

The pyro-electric character has attracted attention since the time of Haüy, who found in 1791 that a cube when heated becomes positively electrified upon four of its corners and negatively upon the remaining four. These differences are very easily shown by Kundt's method of dusting a crystal, after heating, with a mixture of red lead and sulphur, as described on p. 129; the four *o*-corners of the combination of Fig. 582 become covered with red lead during cooling, the remainder (ω) with yellow sulphur.

So far there is nothing contradictory of cubic symmetry ; but it has also been known since the time of Brewster that the mineral is birefringent. A transparent crystal of boracite examined under the microscope transmits light in patches between crossed nicols, and sometimes appears to have a fibrous or lamellar structure ; if sufficiently thin sections be used, they are seen to consist in reality of differently orientated portions of a material which is biaxial with a large axial angle. For example, a thin slice cut parallel to one of the cube-faces shows a more or less distinct division into four fields along the diagonals of the face ; each field exhibits an optic axis (belonging to a biaxial crystal) emerging nearly normal to the cube-face ; twin-lamellations and the interposition of patches differently orientated are also to be seen. The structure appears to differ for the different cube-faces of one crystal, and differs also with the distance from the surface at which the section is cut. The structure has been the subject of numerous investigations and much discussion. According to Mallard, whose opinion is now generally accepted, a crystal of boracite is made up in the following

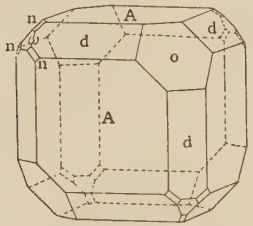


Fig. 582.—Boracite, A {100}, *d* {110}, *o* {111}, ω {1$\bar{1}$1}, *n* {2$\bar{1}$1}.

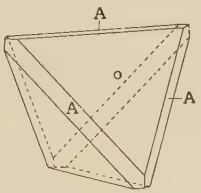


Fig. 583.—Boracite, *o* {111}, A {100}.

way : take a rhombic dodecahedron and imagine it to be constructed of twelve pyramids, each having a dodecahedron-face for base and its apex at the centre of the crystal ; each of these will then be one of the twelve orthorhombic (or monoclinic ?) individuals which go to form a boracite crystal ; the axial plane of each crystal will be parallel to the longer diagonal of the rhombic face, and a bisectrix perpendicular to the face ; the axial angle (2V) being about 90°, one optic axis will be perpendicular to each cube-face. Hence, also, no distinction can be made in this mineral between acute and obtuse bisectrix. The interpenetrating constituent crystals of which a boracite crystal is composed appear to be related by twinning upon planes parallel to the dodecahedral faces of the pseudo-cubic crystal, but they meet along irregular boundaries.

The observations of Mack showed that the pyro-electric property is mainly developed along certain lines which traverse the surface of the crystal, and that these lines are precisely the lines of contact of the twelve sub-individuals whose existence is indicated by the optical properties.

If the section be heated the birefringence of the different portions changes, as is shown by change in the vivid interference-tints, and their boundaries move and often take up different positions when the section is allowed to cool. Mallard made the very interesting discovery that at

a temperature of 265° all these optical differences suddenly disappear; the crystal becomes isotropic, and is dark between crossed nicols; on cooling, however, "optical anomalies," complexity of structure, and twin-lamellation again make their appearance.

The disappearance of birefringence at 265°, and its reappearance at the same temperature on cooling, must be explained by the supposition that boracite is dimorphous, and that the truly cubic form is stable above this temperature; but that at lower temperatures it is converted into a pseudo-cubic modification capable of simulating a cube by twinning.

In view of the pronounced tetrahedral habit of the crystals it would at first sight seem reasonable to suppose that boracite originally crystallised at a high temperature as a cubic mineral with polar symmetry and was transformed on cooling into a twinned intergrowth of a pseudo-cubic (orthorhombic ?) modification. Against this, however, is the remarkable fact that the pyro-electric character disappears above 265°, so that the cubic modification is apparently not polar. Moreover, the association with such minerals as carnallite make it hard to suppose that the temperature of formation can have been so high as 265°. We are therefore driven to the conclusion that the crystals must have been formed from the first as mimetic twins; but the regular arrangement of the tetrahedral and other faces in exact agreement with di-tesseral polar symmetry still needs explanation.

Borax. — Hydrated borate of sodium; $Na_2B_4O_7 . 10H_2O$; $Na_2O = 16{\cdot}3$, $B_2O_3 = 36{\cdot}5$, $H_2O = 47{\cdot}2$.

Monoclinic.

$$a : b : c = 1{\cdot}100 : 1 : 0{\cdot}563. \quad \beta = 73° 25'.$$

$$A = \{100\},\ m = \{110\},\ C = \{001\},\ z = \{22\bar{1}\},\ o = \{11\bar{1}\}.$$

$$AC\ (100) : (001) = 73° 25',\ Am\ (100) : (110) = 46° 30',\ Cm\ (001) : (110) = 78° 40',$$
$$Co\ (001) : (\bar{1}11) = 40° 30',\ Cz\ (001) : (\bar{2}21) = 64° 7'.$$

Cleavage {100}, perfect; {110, good. Brittle. Fracture, conchoidal. H = 2 to $2\frac{1}{2}$; G = 1·7. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}47$, $\alpha = 1{\cdot}45$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}025$. Acute bisectrix perpendicular to (010). Axial plane (Na-light) inclined at 35° to the normal of A and 71° 35′ to the normal of C. $2E = 59° 23'$. Marked crossed dispersion; $\rho > v$. Taste, sweet, alkaline. Intumesces and fuses. Soluble in water.

With the above description compare crystals from **Thibet.**

A considerable number of borates occur in Nature and are interesting on account of their economic importance, being employed for the manufacture of boric acid and borax. Of these compounds **borax** is the most important; it has been for a long time obtained from the salt lakes of Thibet, the waters of which contain borax in solution, and it is now largely worked at the salt lakes of California. In the neighbourhood of the borax lakes at both these localities large crystals of the mineral are found among the shore deposits; these have the same habit and other characters as crystals deposited from aqueous solution in the laboratory and the characters are easily observed in the artificial crystals.

A noteworthy feature of borax is its striking crossed dispersion. The obtuse bisectrix for red light is inclined at 2° to that for blue light, and the dispersion is very easily seen in the interference-figure, which, moreover, is easily brought within the field of view of the microscope, since the axial angle in air is not more than 60°; in examining this figure it must be remembered that not only are the axial planes crossed, but also the angle between the optic axes in air is 3° greater for red than for blue light. The axial plane for red is inclined to the vertical at a larger angle than that for blue.

An important character of borax, and one which gives it great value, is its antiseptic property or power of arresting decay; it has been largely used for the preservation of meat, fish, etc. It is also used in laundry work, as a flux in soldering, and in making optical glass.

Massive borax is a white earthy material, but often coloured by impurities; it is known as "tincal."

The most beautiful mineral among the borates is **colemanite** $HCa(BO_2)_3 . 2H_2O$, discovered in 1882–83 in California; this occurs in lustrous, colourless, transparent crystals resembling calcite, except that the lustre is inclined to adamantine; the mineral is monoclinic and has a perfect cleavage parallel to {010}. The crystals, up to two or three inches in length, occur in geodes in a compact white massive colemanite. A massive white borate occurring in nodules with gypsum, which is worked at Panderma on the sea of Marmora (**pandermite**), and a similar material (priceite) found in steatite in Oregon, have very nearly the composition of colemanite. These minerals are all used for the preparation of borax.

SECTION XIV

THE CARBONATES

THE CALCITE GROUP

Calcite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$
Magnesite	$MgCO_3$
Chalybite (Siderite)	$FeCO_3$
Calamine	$ZnCO_3$
Rhodochrosite (Dialogite)	$MnCO_3$.

Calcite.—Carbonate of calcium; $CaCO_3$; $CaO = 56{\cdot}0$, $CO_2 = 44{\cdot}0$.

Hexagonal; symmetry, dihexagonal alternating.

$$a = 101^\circ\ 55',\quad [a : c = 1 : 0{\cdot}8543].$$

$$\mathrm{R} = \{100\},\ a = \{10\bar{1}\},\ m = \{2\bar{1}\bar{1}\},\ e = \{110\},\ f = \{11\bar{1}\},\ o = \{111\},$$
$$v = \{20\bar{1}\},\ t = \{310\},\ w = \{410\}.$$

$o\mathrm{R} = (111) : (100) = 44^\circ\ 37'$, RR $(100) : (010) = 74^\circ\ 55'$, ee $(110) : (101) = 45^\circ\ 3'$, ff $(11\bar{1}) : (1\bar{1}1) = 101^\circ\ 9'$, vv $(20\bar{1}) : (2\bar{1}0) = 35^\circ\ 36'$, vv $(20\bar{1}) : (02\bar{1}) = 75^\circ\ 22'$, $v\mathrm{R}$ $(20\bar{1}) : (100) = 29^\circ\ 2'$, tt $(103) : (301) = 41^\circ\ 55'$, ww $(104) : (401) = 49^\circ\ 23'$.

Twinned on o (111), e (110), R (100), f $(1\bar{1}1)$. Cleavage R, perfect. Brittle. Fracture, conchoidal. $H = 3$; $G = 2{\cdot}72$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}658$. Birefringence very strong, negative; $\epsilon - \omega = -0{\cdot}172$. Infusible. Soluble, with effervescence, in acids.

With the above description compare crystals from **Egremont** (Cumberland).

Calcite (Germ. *Kalkspath*, Fr. *chaux carbonatée*) is, with the exception of quartz, the most common of all minerals; in most places whither calcareous solutions have penetrated, calcite has been deposited, so that, like quartz, it is a very common occupant of veins. In the form of limestone and marble it occurs massive in enormous quantities both as original deposits and as a metamorphic mineral; as the result of the decomposition of calcium-magnesium silicates in the igneous rocks, calcite crystallises in their cavities and amygdales; as chalk it is one of the most widely distributed minerals of organic origin.

Like quartz again, it is found in the most perfect and beautiful crystals, and has been the subject of as much study on the part of physicists. The

strong double refraction and perfect cleavage attracted the attention of Erasmus Bartholinus (1670), at the exact time when Steno was establishing the constancy of crystal angles on quartz. Bartholinus' book, *Experimenta crystalli Islandici*, contains a very full study of the cleavage-form and the birefringence of the enormous clear crystals which had then been recently discovered in Iceland. These observations, extended by Huygens in 1690, led to the discovery of the laws of double refraction which were developed by the latter. Numerous careful and elaborate observations have since that date been made upon Iceland spar with the object of verifying or disproving Huygens' theory of double refraction. Again, Iceland spar enabled Malus (1808) to discover the polarisation of light, and as the material of the nicol prism and the dichroscope it has acquired great value for optical researches of all sorts.

The varieties of crystalline form of calcite exceed those of all other minerals, and have been more exhaustively studied than any except, perhaps, those of quartz. Count Bournon's treatise on calcite, published in 1808, contains the description of 56 distinct forms, and up to the present time more than 200 have been recorded. The cleavage angle RR = 74° 55′ (Fig. 584) was correctly measured by Wollaston by means of his newly

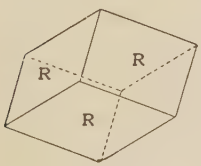


Fig. 584.—Calcite, R {100}.

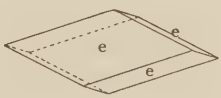


Fig. 585.—Calcite, *e* {101}.

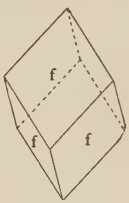


Fig. 586.—Calcite, *f* {1$\bar{1}$1}.

invented reflecting goniometer in 1812; Huygens had determined this angle as 75°; while Haüy, supposing that the two diagonals of the rhombohedron-face must have the simple ratio $\sqrt{3} : \sqrt{2}$, gave the angle as 75° 31′ 20″, in accordance with this supposition.

Four distinct habits of calcite may be recognised: rhombohedral, prismatic, scalenohedral, and tabular. The cleavage-rhombohedron R {100} (Fig. 584) is rather rare as a simple form, but occurs, for example, in fissures of a grey limestone at Poretta near Bologna. The obtuse rhombohedron *e* {110} (Fig. 585), which truncates the edges of R, is quite common; for example, in the lead mines of England. The acute rhombohedron *f* {1$\bar{1}$1} (Fig. 586), whose edges are truncated by R, is also rare, but is the usual form in the sandy calcite or "Fontainebleau sandstone" mentioned on p. 243, and in a similar arenaceous calcite from Vienna.

The common hexagonal prism is *m* {2$\bar{1}\bar{1}$}, which is easily distinguished from the rarer hexagonal prism *a* {10$\bar{1}$} by the fact that the cleavage R removes the edges from the former when combined with the basal pinakoid (*cf.* Fig. 14, p. 14), and the corners from the latter. The prism *m* is terminated either by the basal pinakoid {111} (as in Fig. 13, p. 14) or

(more often) by the rhombohedron *e* (Fig. 587). Sometimes *e* has its lateral edges truncated by the prism *a* (*cf.* Fig. 588).

The common scalenohedron is *v* {20$\bar{1}$}, which is of very frequent occurrence as a simple form, and crystals of this form are known as " dog-tooth spar " (Fig. 589). This form is usually striated parallel to its lateral edges (intersections with {100} or {10$\bar{1}$}).

Tabular crystals are usually the combination *mo* of Fig. 13, p. 14,

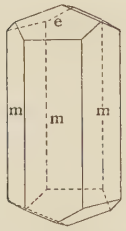


Fig. 587.—Calcite, *m* {2$\bar{1}\bar{1}$}, *e* {101}.

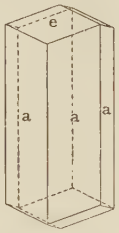


Fig. 588.—Calcite, *a* {10$\bar{1}$}, *e* {101}.

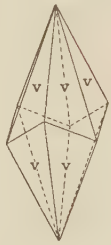


Fig. 589.—Calcite, *v* {20$\bar{1}$}.

flattened so that *m* is quite small; sometimes, and especially in crystals filling thin cavities, they are a combination of the pinakoid *o* with R.

All the above-mentioned forms are very common in combinations, of which there is an endless variety. However complicated these may be, they may usually be deciphered by noting the position of the cleavage-rhombohedron R, whose glittering facets can always, owing to the fragility of the mineral, be traced on some of the edges or corners. R meets *v* in edges parallel to the lateral edges of the scalenohedron itself; truncates the polar edges of *f*; replaces the corners of *e* and of *a*; and meets *m* in horizontal edges.

Fig. 590.—Calcite, {2$\bar{1}\bar{1}$}, *v* {20$\bar{1}$}, R {100}.

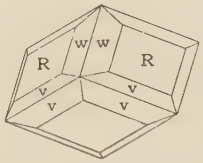


Fig. 591.—Calcite, R {100}, *v* {20$\bar{1}$}, *w* {410}.

The scalenohedral combination of Fig. 590 is a very common type of dog-tooth spar in Derbyshire, in the Harz, and elsewhere.

The rhombohedron R is the predominant form in crystals of " Iceland spar," which are sometimes found of enormous size; these crystals are dull on the surface and have a rounded appearance owing to the bevelment of the terminal edges by *w*, and of the lateral edges by *v* (Fig. 591).

The relations between the various forms mentioned above can be traced on the projection, Fig. 592.

Some of the most brilliant crystals are those from the copper mines of Lake Superior, from the iron mines of Cumberland, and from the Harz Mountains.

The faces on the best crystals are all smooth and bright, but there is often a tendency to striation along the edges of the predominant zone [*eRva*]

by which faces belonging to this zone may be recognised ; *e* in particular is striated parallel to its intersection with R.

Among other combinations found on calcite are acute rhombohedra

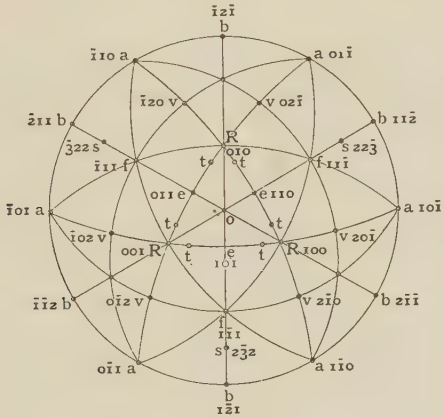


Fig. 592.—Projection of Common Forms of Calcite.
$b=m$ {2$\bar{1}\bar{1}$} ; t={310}.

with the basal pinakoid like the crystal of chalybite shown in Fig. 608, p. 459 (*cf.* Fig. 179, p. 73).

Twinning.—Four well-defined laws are distinguished :

(1) Twin-plane (111).—Two crystals are usually united by juxtaposition along the twin-plane ; in the scalenohedron *v* this introduces an equatorial plane of symmetry indicated by re-entrant angles round the middle of the crystal (Fig. 593), and this type is common among the Derbyshire crystals.

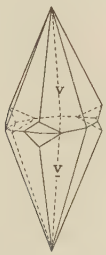


Fig. 593.—Calcite, *v* {20$\bar{1}$}, twinned on (111) or on axis [111].

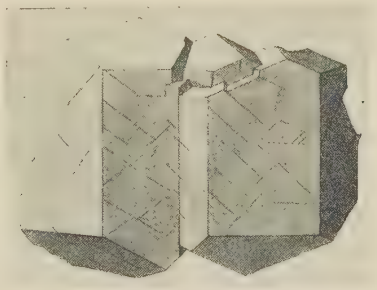


Fig. 594.—Calcite, {2$\bar{1}\bar{1}$}, {101}, twinned on (111) or on axis [111].

But the two individuals often overlap. In crystals of prismatic habit this twinning will be shown by the occurrence of the same forms opposite to one another at the two ends of the crystals instead of in alternate positions. The twinning may equally well be described as due to hemitropy about the vertical axis [111]. Fig. 594 represents a twin (combination *me*) in

which the two individuals are juxtaposed in reversed position and united not along (111) but along a prism-face. Fig. 595 shows the manner in which this twinning is betrayed by the cleavage.

(2) Twin-plane (100).—Two crystals thus twinned have their principal

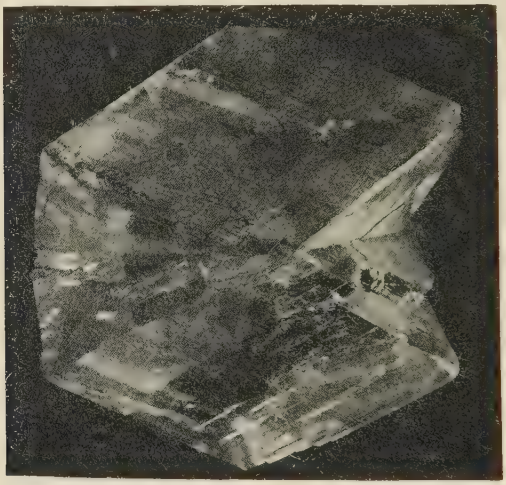


Fig. 595.—Calcite, cleavage from crystal twinned on (111) (British Museum).

axes nearly at right angles to each other; the angles are actually 89° 14′ and 90° 46′, since $o\mathrm{R} = 44° 37'$. This mode of twinning is common both in crystals of prismatic habit (Fig. 596) and in scalenohedral crystals (Fig. 597). It can always be easily identified on consideration of the fact

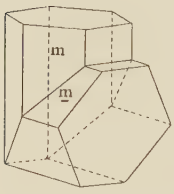


Fig. 596. — Calcite, m {2$\bar{1}\bar{1}$}, {111}, twinned on (001).

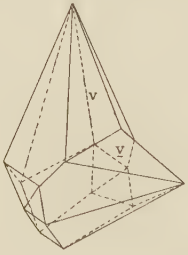


Fig. 597. — Calcite, v {20$\bar{1}$}, twinned on (001).

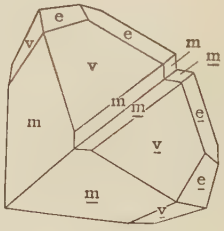


Fig. 598.—Calcite, m {2$\bar{1}\bar{1}$}, v {20$\bar{1}$}, e {110}, twinned on (001).

that the twin-plane is a cleavage plane, so that one cleavage, and only one, is parallel in the two individuals. When the crystals are of scalenohedral habit they usually show an extension of two pairs of the faces v, so as to fill up the angle between the two individuals, and give rise to curious butterfly- or heart-shaped doublets (Fig. 598). These so-called " butterfly

twins " were formerly found at Eyam in Derbyshire and more recently at Egremont in Cumberland.

(3) Twin-plane (110).—Here, since $oe = 26° 15'$, the principal axes meet at angles of 52° 30′ and 127° 30′. Although this law is the most usual of the four, juxtaposed twins in which the crystals are united along the twin plane, and meet at an angle of 127° 30′, are not very common ; but twins of this sort (Fig. 599) have been found in abundance at Guanaxuato in Mexico. In these again there is a remarkable enlargement of two pairs of faces of the scalenohedron *v*, giving the doublet a very misshapen appearance. More commonly the two individuals are united along a plane perpendicular to the twin-plane, and their axes make an angle of $52\frac{1}{2}°$, while a pair of cleavages in one crystal are parallel to a pair of cleavages in the other and reflect light simultaneously with them. The twin-plane *e*, which would truncate the edge of this pair of cleavages in one crystal, is parallel to the corresponding plane on the other. From

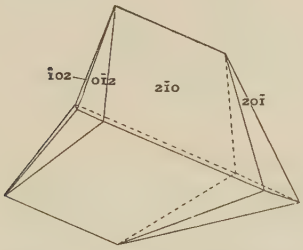


Fig. 599.—Calcite, {20$\bar{1}$}, twinned on (110).

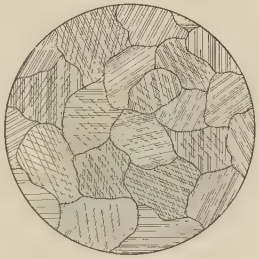


Fig. 600.—Section of marble, showing twin-lamellæ {110} of Calcite.

the side of one crystal a smaller crystal is often seen to emerge in this way, with two cleavages reflecting simultaneously with the larger crystal. More commonly still this twin-law reveals itself by the existence of twin-lamellæ parallel to *e*, and these appear to be often of secondary origin ; the artificial twinning of calcite by gliding along *e* has been described on p. 106. The effect of pressure is to produce such lamellæ in any crystal of calcite, and much calcite lining fissures or cavities in rocks has been probably subjected to pressure, and is traversed by such lamellæ. In thin sections made for the microscope they are so characteristic as to serve for the identification of calcite. Fig. 600 represents a section of marble or granular limestone, in which each grain shows the characteristic lamellæ of secondary twinning parallel to *e*.

(4) Twin plane (11$\bar{1}$).—The two individuals here intersect at angles of 53° 46′ and 126° 14′, since the angle $of = 63° 7'$. A twin, like Fig. 601, in which *f* is also the plane of composition, will therefore very closely resemble a twin of the last class, in which composition is perpendicular to the twin-plane *e*, for in each case the two individuals are inclined at about 53°. In the twins on the present law, however, cleavage-planes are no longer parallel in the two individuals, since *f* does not truncate RR ;

but two cleavage-planes meet at an angle of 35° 27′ across the plane of composition. It will be seen from Fig. 601, and from the projection,

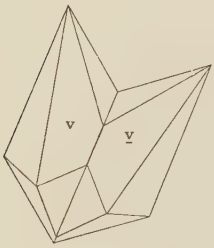


Fig. 601.—Calcite, v {20$\bar{1}$}, twinned on ($\bar{1}$11).

Fig. 602.—Calcite, {2$\bar{1}\bar{1}$}, {110}, twinned on ($\bar{1}$11), from Egremont (British Museum).

Fig. 592, that the plane of composition f truncates the acute edge of the scalenohedron v, since $(20\bar{1}) + (02\bar{1}) = (11\bar{1})$. Hence in Fig. 601 two obtuse edges of the scalenohedron face one another in the acute angle between

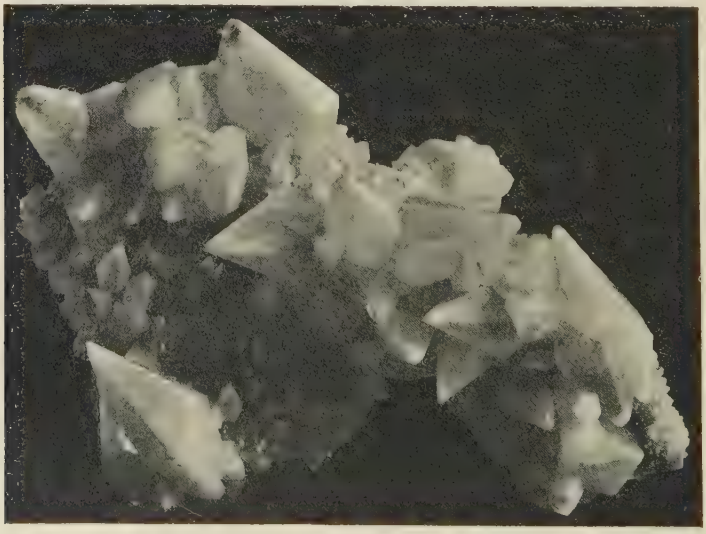


Fig. 603.—Calcite from Guanaxuato (British Museum).

the individuals; in a twin according to the third law, two acute edges would face one another.

All the above four laws are illustrated by the beautiful crystals found at Egremont in Cumberland.

Fig. 603 represents a typical group of scalenohedral calcite from

Guanaxuato. Fig. 604 is a group from Wheal Wrey near Liskeard, where

Fig. 604.—Calcite from Wheal Wrey (British Museum).

specimens of great beauty were formerly found; the crystals resemble trigonal prisms, but are really very acute rhombohedra combined with *o*,

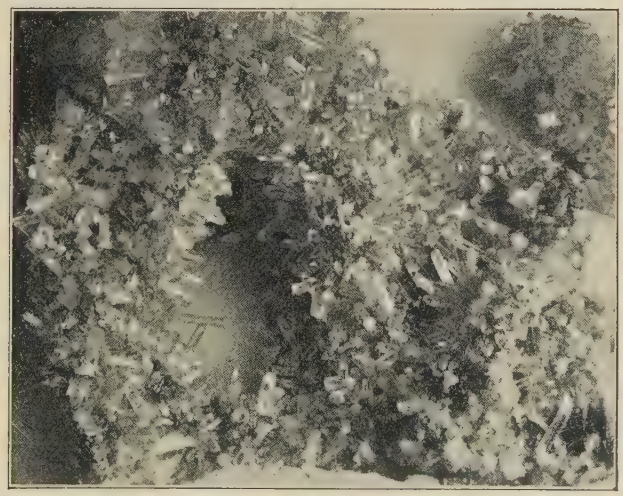


Fig. 605.—Calcite from Egremont (British Museum).

and are mostly twinned on R, like Fig. 596. Fig. 605 is a beautiful group of prisms from Egremont—a locality which has furnished so many varieties.

The hexagonal bipyramid of Fig. 182, p. 75, the particular case of a scalenohedron in which the faces are equally inclined to two adjacent planes of symmetry, is extremely rare. Crystals showing faces of such forms have been found at Rhisnes in Belgium and Visby in Sweden, with the indices $\{91\bar{7}\}$.

Special names have been given to some of the more peculiar habits of calcite. "Dog-tooth spar" (Fig. 589) and "nail-head spar" (Fig. 223, p. 95) have been already mentioned; "slate spar" (Germ. *Schieferspath*) is a thin tabular variety due to predominance of the basal pinakoid; the plates are sometimes as thin as paper, and often grouped parallel to one another; this platy structure may give rise to an apparent cleavage or parting parallel to $\{111\}$.

The conchoidal fracture mentioned on p. 314 (Fig. 458) is difficult to obtain owing to the facility of the R-cleavage. There is often also a parting parallel to *e* in crystals which have undergone pressure, owing to gliding and secondary twinning along that plane.

A very remarkable feature due to this twinning is presented by some calcite; when a candle flame is viewed through certain crystals or cleavage-fragments it appears as a radiating star of light: this effect is known as "asterism"; it is also exhibited by some mica and labradorite, and in those minerals is due to minute enclosures arranged in certain definite directions. The asterism of calcite is due to systems of minute hollow canals which seem to have been produced where the gliding surfaces *e* intersect one another; these are parallel to each other in three directions.

The use of calcite as the material of nicol prisms is made possible by the fact that of its two principal indices, ω (1·658) is much greater, and ϵ (1·486) is somewhat less than the index of Canada balsam (1·536); this causes the ordinary ray to be totally reflected by a suitably inclined film of balsam, while the extraordinary ray passes through (*cf.* p. 145). Owing to the same cause a microscopic section of calcite mounted in Canada balsam, when rotated on the stage above the polariser (without using the analyser), shows in one position a high relief, and (usually) a much lower one when turned through a right angle, since in one position the transmitted light consists of the ordinary and in the other position of the extraordinary rays. This effect, which is quite different from pleochroism, is sufficient to identify calcite (or dolomite) in thin sections of rocks. It is most striking in sections so cut that the refractive index for the extraordinary ray is equal to that of balsam.

The structure of calcite has already been described (p. 295).

Some Noteworthy Localities:

Eskifjördhr (Iceland).—This is the locality of the famous "Iceland spar." A cavity in the dolerite about 36 feet by 15 feet in area and 10 feet high was filled with clear crystallised calcite; the crystals are of two habits, either rhombohedra $\{100\}$ with edges bevelled by $\{410\}$ and $\{20\bar{1}\}$, like Fig. 591, or scalenohedra $\{20\bar{1}\}$ terminated by $\{410\}$, $\{100\}$.

The crystals are dull and somewhat corroded on the surface and often coated with crystals of stilbite. Some of the calcite crystals

were of enormous size; one in the British Museum is about $2\frac{1}{2}$ feet by $1\frac{1}{2}$ feet.

Derbyshire.—In the veins of the Carboniferous limestone fine crystals of scalenohedral habit used to be found in the neighbourhood of **Matlock, Eyam,** etc., often associated with galena and fluor. Among these the (111) twin, like Fig. 593, and the heart-shaped (100) twins, like Fig. 598, are especially noteworthy.

North of England.—In the lead mines of **Alston** (Cumberland), and of **Weardale** (Durham), in the iron mines of **Furness** (Lancashire), and **Egremont** (Cumberland), fine specimens have been found, often of prismatic habit and often scalenohedral, and generally showing faces of *e* {110}, which are striated parallel to their intersections with R {100}. An acute rhombohedron $\{3\bar{1}\bar{1}\}$ may often be discerned among the forms present among north of England calcites. The crystals discovered at Egremont in 1888 were found in cavities in the Carboniferous limestone, associated with a soft earthy hæmatite and consequently very fully developed and easy to detach; they illustrate many varieties of habit and all the four twin laws. Fig. 605 shows a large and beautiful group of crystals, of prismatic habit $\{2\bar{1}\bar{1}\}$, terminated by {100}, {110}, in the British Museum; other crystals are very acute rhombohedra, like Fig. 608 of chalybite; others, again, very acute scalenohedra which look like sharp hexagonal bipyramids. Among the twins are large heart-shaped twins on (100), like those from Eyam in Derbyshire (Fig. 598), and also the rare twin on *f* $(11\bar{1})$, shown in Fig. 602.

Andreasberg (Harz Mountains).—A great variety of beautiful specimens have been found in the mines of this district in the metalliferous veins in clay-slate, where the calcite accompanies ores of lead, silver, and arsenic, together with zeolites. Crystals of prismatic and tabular habits are common, especially combinations of *m* $\{2\bar{1}\bar{1}\}$ and *e* {110}. The basal pinakoid {111} is usually dull.

Joplin (Missouri).—Beautiful, clear, honey-yellow scalenohedra, *v* $\{20\bar{1}\}$ terminated by R {100} and striated faces of *e* {110}, are here obtained; the more acute terminal edges of *v* are sometimes replaced by striated and rounded faces, and among other forms are various flat scalenohedra modifying the edges R*e*.

Dolomite.—Carbonate of calcium and magnesium; $CaMg(CO_3)_2$; $CaO = 30{\cdot}4$, $MgO = 21{\cdot}9$, $CO_2 = 47{\cdot}7$.

Hexagonal; symmetry, hexagonal alternating.

$$a = 102^\circ\ 38', \quad [a : c = 1 : 0{\cdot}8322].$$

$$R = \{100\},\ o = \{111\}.$$

$$oR\ (111) : (100) = 43^\circ\ 51\tfrac{1}{2}', \quad RR\ (100) : (010) = 73^\circ\ 45'.$$

Twinned on the vertical axis [111]. Cleavage {100}, perfect. Brittle. Fracture, sub-conchoidal. $H = 3\frac{1}{2}$; $G = 2{\cdot}87$. Colourless. Streak, white, Lustre, vitreous. Transparent; $\omega = 1{\cdot}682$. Birefringence very strong, negative; $\epsilon - \omega = -0{\cdot}189$. Infusible. Soluble with effervescence in warm hydrochloric acid.

With the above description compare crystals from **Binnenthal** (Switzerland).

Dolomite (Germ. *Bitterspath*) is especially interesting for two reasons: (1) because it belongs to the dioptase, and not to the calcite class, having hexagonal, and not dihexagonal, alternating symmetry; (2) because it is often regarded as a double salt, in which calcium carbonate and magnesium carbonate are united in molecular proportions, and not as an isomorphous mixture of calcite with magnesite. The absence of planes of symmetry is proved by the etching- and elasticity-figures (see Figs. 278, 282, pp. 122, 125), and also by the occasional appearance of six facets situated unsymmetrically on the corners of the primary rhombohedron R {100}. These, like the faces *s* in Fig. 193, constitute a second rhombohedron, instead of a scalenohedron as in calcite, and prove that the faces R are not perpendicular to planes of symmetry. The absence of the planes of symmetry is also characteristic of the structure of dolomite, as described on p. 296.

Dolomite is very commonly twinned by hemitropy about the vertical

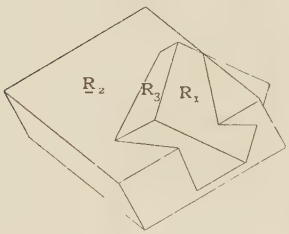


Fig. 606.—Dolomite, R {100}, twinned on axis [111].

Fig. 607.—Dolomite on Fluor, from Liskeard.

axis of symmetry [111]; the two rhombohedra interpenetrate, as in Fig. 606. Other twin-laws are also known, but are rare; among them is supplementary twinning which gives the crystal the di-hexagonal symmetry of calcite. Another respect in which dolomite differs from calcite and magnesite is that *e* {110} is not a gliding plane or plane of secondary twinning. The lustre of dolomite is often somewhat pearly; the faces are very frequently curved, the crystals being built up of numerous small rhombohedra in nearly parallel positions. Fig. 607 represents a specimen of pearly dolomite upon cubes of fluor spar from the Menheniot mines near Liskeard (Cornwall); the dolomite crystals are here doubly curved, so that they become saddle-shaped, and they have a characteristic scaly texture.

Massive dolomite, like limestone, is found in large beds constituting whole tracts of country (*e.g.* the magnesian limestone in North England) or mountain ranges, as in the "dolomite" region of the Tyrol; much of the latter is in reality limestone. The white granular crystalline dolomite of the Binnenthal in Switzerland, which resembles loaf-sugar, is well

known as the source of beautifully crystallised blende, realgar, and many sulpharsenites, and small colourless crystals of dolomite (with R and *o*) are found in its cavities; the massive mineral is traversed by thin threads of pyrites (see Fig. 506) in the neighbourhood of these metallic minerals. Large isolated interpenetration twins, like Fig. 606, are obtained from Traversella in Piedmont. Another noteworthy occurrence of dolomite is that in *black*, acute, direct rhombohedra, like Fig. 608, which are found in anhydrite at Hall in the Tyrol.

Chalybite.—Carbonate of iron; $FeCO_3$; $FeO = 62{\cdot}0$, $CO_2 = 38{\cdot}0$. Hexagonal; symmetry, di-hexagonal alternating.

$$a = 103° 4', \quad [a : c = 1 : 0{\cdot}8186].$$

$$R = \{100\}, \; o = \{111\}.$$

$$oR\,(111) : (100) = 43° 23', \; RR\,(100) : (010) = 73° 0'.$$

Twinned on *e* (110). Cleavage {100}, perfect. Brittle. Fracture, subconchoidal. $H = 3\frac{1}{2}$; $G = 3{\cdot}86$. Brown. Streak, white. Lustre, vitreous. Translucent; $\omega = 1{\cdot}873$. Birefringence very strong, negative; $\epsilon - \omega = -0{\cdot}241$. Fuses ($4\frac{1}{2}$) to black magnetic globule. Soluble with effervescence in warm hydrochloric acid.

With the above description compare crystals from **Neudorf** (Harz).

Chalybite (Germ. *Braunspath*) is one of the common ores of iron, and is found in good crystals in many metalliferous veins, as at Freiberg, in the Harz, and in Cornwall. Like dolomite it usually occurs in the

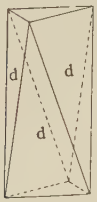


Fig. 608. — Chalybite, *d* {533}, {111}.

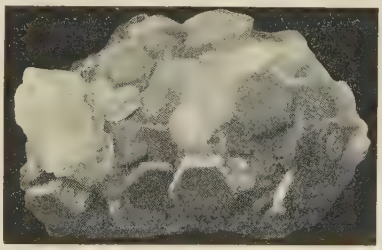


Fig. 609.—Chalybite on Quartz, from Lostwithiel (British Museum).

simple rhombohedra {100}, which are comparatively rare in calcite. But the habit is very variable. Acute rhombohedra like Fig. 608 ($d = \{5\bar{3}\bar{3}\}$), with or without the basal plane, are not uncommon. Fig. 609 represents a tabular variety formerly found at Wheal Maudlin, near Lostwithiel, in Cornwall, to be seen in many collections. It consists of brown crystals with large curved faces of {111} and drusy rhombohedron and prism faces showing a distinct zonal structure marked by hexagonal bands of different shades on the basal plane. The twinning of chalybite is chiefly visible as lamellæ parallel to {110}.

This mineral is sometimes not only acute in habit, like Fig. 608, but even fibrous, and, like most fibrous minerals, tends to botryoidal and globular forms. "Clay-ironstone," an impure argillaceous chalybite, which in the coal measures of Staffordshire, Yorkshire, and Wales, was formerly the most important iron ore of England, is frequently found concretionary and in globular masses; these are sometimes called "sphærosiderite."

Chalybite is liable to oxidation and hydration and passes into deep brown or black limonite. Very perfect pseudomorphs of limonite after chalybite have been found at Traversella in Piedmont; dehydration then leads to the formation of hæmatite or magnetite; some dark chalybite acts feebly on the magnetic needle.

The calcite group is perhaps the best-defined group among minerals; its members all crystallise in the rhombohedral system with the same type of structure (p. 295), their common forms are very similar, they all have a perfect cleavage parallel to the faces of a rhombohedron of about 75°, and they form a large series of isomorphous mixtures.

As might be expected from the metals which they contain, they differ widely in colour. Calcite, dolomite, magnesite, and calamine, when pure, are colourless; chalybite is grey (or more often brown, owing to oxidation of the iron); rhodochrosite, a delicate pink; and the isomorphous mixtures show a great variety of tints. They are easily distinguished from minerals of similar appearance which are not carbonates by their brisk effervescence with acids (dolomite, chalybite, and magnesite only with warm acids), and from other carbonates by their cleavage.

Dolomite, the mineral of less symmetrical composition, is the only one whose symmetry has been proved to belong without doubt to the dioptase type; the etching figures of magnesite and chalybite point to the possibility of their belonging to the same class. It is of course possible that the whole group is really hexagonal alternating, and not di-hexagonal, but liable to supplementary twinning, and that in dolomite alone the usual absence of this twinning discloses the true symmetry.

Dolomite, even if it be a double salt, appears to be isomorphous with the others and contains intermixed chalybite, calamine, and rhodochrosite; even those specimens which contain only calcium and magnesium vary much in composition owing to intermixture with calcite and magnesite.

Rhodochrosite (Germ. *Manganspath*) is not often found well crystallised; beautiful pink rhombohedra {100} with iron pyrites have been found at Alicante in Colorado; this mineral also occurs in acute scalenohedra.

Calamine (Germ. *Zinkspath*, *Galmei*), which is colourless when pure, but is more usually green, blue, or brown, owing to the intermixture of other carbonates (?), is also rare in crystals, and tends, like chalybite, to botryoidal forms. Particularly remarkable are white earthy spherical concretions found in the zinc mines of Santander in Spain.

Intermixtures of all the rhombohedral carbonates are very common; the pure minerals are rare. That $CoCO_3$ belongs to the same series is

proved by the presence of cobalt in some rhodochrosite and dolomite, and a red botryoidal substance found at Schneeberg in Saxony, and named **sphærocobaltite**, has the composition $CoCO_3$ and appears to consist of minute rhombohedra.

Special names have been given to many of the mixtures by Breithaupt and others: "mesitite" (*i.e.* the midway mineral) to the pale brown obtuse rhombohedra of Traversella, whose composition is $2MgCO_3 . FeCO_3$; "pistomesite" (the truly midway mineral) to brown crystals from Salzburg which were found to have the composition $MgCO_3 . FeCO_3$; "ankerite" to varieties approximating to $2CaCO_3 . MgCO_3 . FeCO_3$; "breunnerite" to the ferriferous magnesite from the Greiner in the Tyrol. But dolomite is the only one which can be at all definitely distinguished as a double salt.

"Brown spar" is a name conveniently used for the brown ferriferous Ca-Mg-carbonates; "pearl spar" for the paler coloured varieties with pearly lustre which usually approximate to the composition of dolomite. Both of these frequently have curved faces and form saddle-shaped crystals like Fig. 607. In these, as in chalybite and dolomite, even the cleavage surfaces are usually curved. These minerals of the calcite-dolomite-chalybite series are common as constituents of metalliferous veins and as associates of iron ores. **Magnesite** occurs commonly as a decomposition product of the ferro-magnesian silicates; thus the white patches in serpentine consist mainly of a compact magnesite. Calamine occurs in more isolated localities, where it is worked as an important ore of zinc, *e.g.* in the zinc mines of Siberia, Aachen, Santander, etc.; in the Derbyshire mountain-limestone it occurs in pseudomorphous crystals after calcite. Blende is sometimes altered into a white earthy calamine.

The lead present in calcite from Wanlockhead, the barium and strontium present in some other calcites, and the cadmium, which sometimes imparts a yellow colour to calamine, indicate that $PbCO_3$, $BaCO_3$, $SrCO_3$, $CdCO_3$ also belong to the series of rhombohedral carbonates.

THE ARAGONITE GROUP

		a	*b*	*c*
Aragonite	$CaCO_3$	0·623	1	0·721
Strontianite	$SrCO_3$	0·609	1	0·724
Witherite	$BaCO_3$	0·603	1	0·730
Cerussite	$PbCO_3$	0·610	1	0·723
Alstonite	$(Ba,Ca)CO_3$	—		

Aragonite.—Carbonate of calcium; $CaCO_3$; $CaO = 56·0$, $CO_2 = 44·0$. Orthorhombic; holosymmetric (?).

$$a : b : c = 0·623 : 1 : 0·721.$$

$$B = \{010\},\ m = \{110\},\ C = \{001\},\ p = \{111\},\ k = \{011\}.$$

$$mm\ (110) : (1\bar{1}0) = 63°\ 48',\ kk\ (011) : (0\bar{1}1) = 71°\ 34'.$$

Twinned on *m* (110). Cleavage {010}, {110}, imperfect. Brittle. Fracture sub-conchoidal. H = 3½; G = 2·94. Colourless. Streak, white. Lustre, vitreous.

Transparent; $\beta = 1{\cdot}682$, $\alpha = 1{\cdot}530$. Birefringence very strong, negative; $\gamma - \alpha = 0{\cdot}156$. Axial plane (100); acute bisectrix perpendicular to (001). $2E = 30°\ 53'$; $\rho > v$. Infusible. Soluble in acids with effervescence.

With the above description compare crystals from **Bilin** (Bohemia).

Aragonite, so called from the locality in Spain where it was first found, is interesting as the earliest and best-established instance of dimorphism in the mineral kingdom, having the same composition as calcite. The crystals generally resemble hexagonal prisms, or are tabular, as in Fig. 610, when the faces B are large in comparison with *m*, and they are sometimes terminated by the basal pinakoid alone.

In several localities aragonite adopts an acute pyramidal habit, due to the predominance of pyramids such as {441} or {991}, and forms such as {081} and {091}. These are usually striated horizontally. Fig. 612 represents a fine specimen from Cleator in Cumberland, in the British Museum.

Simple forms are rare; some of the single crystals from Bilin present

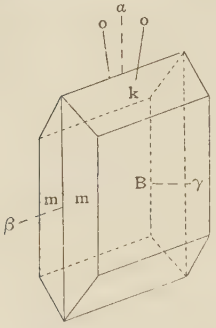


Fig. 610.—Aragonite, B {010}, *m* {110}, *k* {011}.

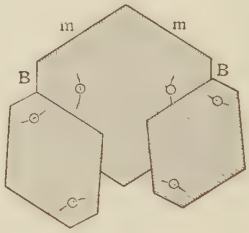


Fig. 611.—Aragonite Triplet twinned on *m* {110}.

the combination of Fig. 610; more usually they are twins or triplets, as in Figs. 248-250 and 256-258. Beautiful examples like Fig. 258 have been found at Girgenti in Sicily, and at Herrengrund in Hungary. Complex crystals betray their twin nature not only by re-entrant angles on the prism-faces and by the striations on C parallel to the edge CB, but also, in thin section, by the different orientation of the optic axes—as shown in Fig. 611; as the section is moved across the microscope stage these are seen to change their position. (See also p. 204.) These pseudo-hexagonal groups are usually somewhat irregular, as shown in Fig. 613, and sometimes the faces C do not quite fall into one plane.

The usual type of the crystals from Aragon is shown in the triplet of Fig. 258, where, since the prism-angle is 63° 48′, there is a re-entrant angle of 11° 24′ on two opposite faces of the apparently hexagonal prism. In the Sicilian and Bohemian crystals the interstices shown in Fig. 256 are often filled by the intercalation of a fourth or fifth individual. Some etching

experiments on aragonite indicate that the symmetry may really be polar ; if this be so the apparently simple crystals are themselves supplementary twins.

Aragonite is far less common than calcite ; solutions of calcium carbonate in water containing CO_2 have been found to deposit calcite when cold, whereas hot solutions deposit aragonite or a mixture of aragonite with calcite ; and some of the natural occurrences are to be traced to deposition from hot solutions. It is also less stable at ordinary temperatures than calcite ; crystals of aragonite have been found altered to calcite ; such cases of pseudomorphism without any chemical change are known as " paramorphs."

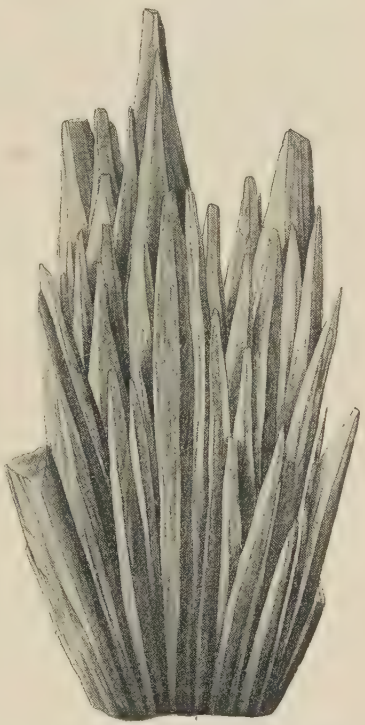


Fig. 612.—Aragonite from Cumberland (British Museum).

Through a cleavage-flake of calcite, or any of the rhombohedral carbonates, the rings surrounding the optic axis are seen at the edge of the field of view in convergent light ; fragments of aragonite usually show an obtuse positive bisectrix.

Many concretionary, botryoidal, and stalactitic forms of carbonate of lime, especially such as are fibrous, consist of aragonite ; such are the " pisolites," or spherical concretions (Germ. *Sprudelstein*, *Erbsenstein*), deposited from the hot springs of Carlsbad in Bohemia (see Fig. 452, p. 309), and the beautiful white coralline stalactites known as *flos-ferri*, of which the best specimens come from the iron mines of Eisenerz in Styria (see Fig. 453, p. 310).

In the absence of recognisable cleavage massive calcite and aragonite may be distinguished by boiling the powdered mineral with a dilute solution of cobalt nitrate ; aragonite becomes lilac-red, whereas calcite becomes lavender-blue, or remains white or yellowish if traces of iron be present.

Some Noteworthy Localities :

Girgenti (Sicily).—Large white, yellowish or brown prisms, twinned, and showing the characteristic striæ on the basal plane, are associated with sulphur and small prisms of celestite. This occurrence has been described under sulphur (p. 349). The crystals found at Herrengrund in Hungary are similar in habit, but are white ; they occur on a granular calcite and are also associated with celestite.

Molina (Aragon, Spain).—The prisms or groups of prisms, Fig. 613, are usually brown or red in colour and very much corroded on the basal planes; they are found in a red ferruginous marl together with gypsum; small red crystals of ferruginous quartz are sometimes dispersed on the aragonite.

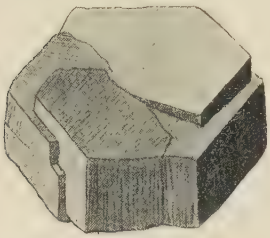


Fig. 613.—Aragonite Triplet from Aragon.

Aragonite, indistinguishable from that of Aragon, is found under the same conditions on the other side of the Pyrenees, at Bastennes in the south of France.

Horschenz (near Bilin, Bohemia).—Transparent yellowish or pale green aragonite is found as isolated crystals in a soft calcareous material which fills large cavities in an olivine-basalt, or lines druses of fibrous aragonite in the same. Some of these are doubly terminated and are either single crystals of the habit of Fig. 610, or examples of the different twins and triplets described above.

Two other members of the aragonite group occur commonly in good crystals, namely cerussite and witherite.

Cerussite.—Carbonate of lead; $PbCO_3$; $PbO = 83{\cdot}5$, $CO_2 = 16{\cdot}5$. Orthorhombic; holosymmetric.

$$a : b : c = 0{\cdot}610 : 1 : 0{\cdot}723.$$

$$B = \{010\},\ m = \{110\},\ p = \{111\},\ i = \{021\}.$$

mm (110) : ($1\bar{1}0$) = 62° 46′, Bi (010) : (021) = 34° 40′, pp (111) : ($1\bar{1}1$) = 50° 0′, pm (111) : (110) = 35° 46′.

Twinned on (110), also on (130). Cleavage {110}, {021}, imperfect. Brittle. Fracture, conchoidal. H = 3½; G = 6·5. Colourless. Streak, white. Lustre, adamantine. Transparent; $\beta = 2{\cdot}076$, $\alpha = 1{\cdot}804$. Birefringence, very strong, negative; $\gamma - \alpha = 0{\cdot}274$. Axial plane (010); acute bisectrix perpendicular to (001). $2E = 17° 8'$; $\rho > v$. Soluble in nitric acid.

With the above description compare crystals from **Mies** (Bohemia).

The aragonite group not only constitutes a series dimorphous with the calcite group, but each member of it is pseudo-hexagonal and simulates the form of the latter by repeated twinning.

Among these minerals **cerussite** (Germ. *Weissbleierz*) occurs in the best crystals; its faces are often very bright and smooth, and it displays the characteristic twinning better even than aragonite. Its habit is very varied, and its forms many; most usual are crystals of pyramidal habit, like Fig. 614, or of tabular habit, like Fig. 610 of aragonite. The latter, when twinned, often form stellate and cruciform groups, in which the spaces between the individuals are not filled in (Fig. 615). Here, as in the interpenetrant aragonite twins of Fig. 257, the prism-faces m of the adjacent crystals which are in twin-position (I and II, II and III) fall into one plane, and reflect light together, while those of the remaining

pair of crystals (I and III) form a slight re-entrant angle ; and the same is true of the adjacent pyramid-faces p. By this characteristic twinning cerussite crystals may often be recognised.

In a pseudo-hexagonal zone, such as the prism-zone of this group, where the angle (110) : (1$\bar{1}$0) is about 60°, the axial ratio $a : b$, as determined by the face (110), is approximately $1 : \sqrt{3}$; a face (130) will therefore intersect the axes with intercepts $\frac{a}{1} : \frac{b}{3}$, or nearly $\sqrt{3} : 1$, and must belong to a prism in which the angle (130) : ($\bar{1}$30) is also about 60°. In such cases it is usual to find that both the pseudo-hexagonal prisms may be planes of twinning. Cerussite is usually twinned on (110), but also, though rarely, on (130).

In the similar case of chrysoberyl (p. 443), the two forms have so nearly the same angle that it is almost impossible to say which is the twin-plane.

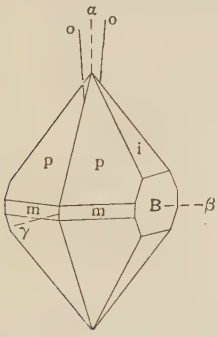


Fig. 614.—Cerussite, B {010}, p {111}, m {110}, i {021}.

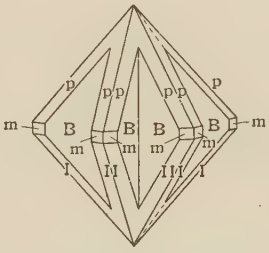


Fig. 615.—Cerussite Triplet, B {010}, p {111}, m {110}, twinned on m {110}.

In cerussite the angle of {110} is 62° 46′, and that of {130}, 57° 19′, so that it is easy to distinguish between them. Twinning on (130) has not been observed on other members of the aragonite group.

Cerussite is found not only in brilliant translucent crystals of tabular, prismatic, and pyramidal (sometimes acute) habits, but also in acicular or fibrous masses which are dead white and opaque ; the best fibrous specimens were formerly found at Pentire Glaze mine, near St. Minver in Cornwall (Fig. 441, p. 305). These will hardly be recognised at first sight as cerussite, but they possess the characteristic adamantine lustre, inclining to resinous, which belongs to so many minerals containing lead.

The finest specimens of cerussite are from the Friedrichssegen mine near Ems in Nassau, and from Mies in Bohemia, where they occur in metalliferous veins upon galena and quartz. Large crystals of various colours, including green, have been found in the lead mines of Nerchinsk in Siberia. Large, white, twinned groups of arrow-head form come from the Broken-Hill silver mines in New South Wales, where they are associated with ores of copper and silver. Cerussite is one of the important ores of lead, and is found in most lead mines as a decomposition product of galena.

Witherite.—Carbonate of barium ; $BaCO_3$; $BaO = 77{\cdot}7$, $CO_2 = 22{\cdot}3$. Orthorhombic ; holosymmetric.

$$a : b : c = 0{\cdot}603 : 1 : 0{\cdot}730.$$

$$m = \{110\},\ B = \{010\},\ k = \{011\},\ i = \{021\}.$$

Twinned on (110). Cleavage {010}, {110}, imperfect. Brittle. Fracture, uneven. H = 3½ ; G = 4·3. Colourless. Streak, white. Lustre, vitreous. Translucent ; $\beta = 1{\cdot}676$, $\alpha = 1{\cdot}529$. Birefringence, very strong, negative, $\gamma - \alpha = 0{\cdot}148$. Axial plane (010) ; acute bisectrix perpendicular to (001). $2E = 26°\ 24'$; $\rho > v$. Fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Hexham** (Northumberland).

Strontianite and **witherite** are comparatively rare minerals, but are important sources of strontium and barium compounds ; the former are much used for fireworks and in the separation of sugar from molasses, the latter for rat poison. The element strontium was first discovered in the strontianite from Argyllshire in 1791 ; at Strontian the mineral occurs as fibrous pale green or brownish masses, rarely terminated. Acute white pyramids of strontianite, horizontally striated like those of aragonite, are found in the lead mines of Pateley Bridge in Yorkshire. Still better acute crystals have been found in veins in a calcareous marl at Hamm in Westphalia.

Strontianite closely resembles aragonite in its varieties of habit (Figs. 610 and 612 of aragonite), and its twinning, but is seldom found in well-defined crystals, occurring usually in fibrous or columnar masses or steep pyramidal forms.

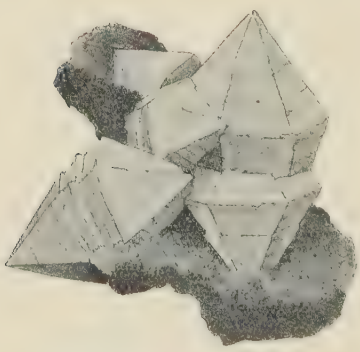


Fig. 616.—Witherite from Hexham.

We have seen that interpenetrant triplets of aragonite form pseudo-hexagonal prisms; crystals of witherite are invariably of pyramidal habit, and form pseudo-hexagonal bipyramids, Fig. 616. A cross-section of a witherite crystal viewed in convergent light is seen to consist of sectors, having three or more different orientations, somewhat as in aragonite (*cf.* Fig. 388). But in witherite the "bipyramid" is commonly formed by faces of {021}, and, as in cerussite, the plane of the optic axes is (010), whereas in aragonite it is (100).

The best specimens of witherite have been found at the Fallowfield lead mine at Hexham in Northumberland ; they occur in veins traversing the carboniferous limestone, and are white hexagonal bipyramids (Fig. 616), sometimes an inch or more in diameter, associated with galena, and often surrounded by steeper hexagonal bipyramids of alstonite. The crystals are sometimes rounded at the apex, owing to the presence of flatter pyramids. They often have a greasy lustre on the surface, or a dull white colour owing to a superficial coating of barytes. The neighbouring

lead mines of Alston Moor in Cumberland yield similar crystals. The mineral discovered and analysed by Withering in 1783 was a fibrous variety from Anglesark in Lancashire.

Isomorphous mixtures are not so common in the aragonite as in the calcite group. Strontianite usually contains some $CaCO_3$; the aragonite from Tarnowitz in Silesia contains as much as 9 per cent of $PbCO_3$; the cerussite from Monte Poni contains 7 per cent of $ZnCO_3$; a little strontium is also found in some aragonite.

The mineral **alstonite**, mentioned above, occurs in small pseudo-hexagonal bipyramids, resembling those of witherite but more acute {221} and sometimes of a pink tint, at Brownley Hill Mine, near Alston, and corresponds somewhat to dolomite in the calcite group. While generally regarded as an isomorphous mixture $(Ba,Ca)CO_3$, its composition usually approximates to $CaCO_3 . BaCO_3$, and its specific gravity, 3·706, is slightly higher than would correspond to a mixture of aragonite and witherite in these proportions, so that it may be a double salt; but it varies considerably in composition, perhaps owing to isomorphous mixture of this double salt with aragonite or witherite.

RELATION BETWEEN THE CALCITE AND ARAGONITE GROUPS

From the preceding pages it is clear that the carbonates of Ca, Mg, Ba, Sr, Fe, Co, Mn, Zn, Pb, are to be regarded as isodimorphous and capable of forming isomorphous mixtures, both in their hexagonal and orthorhombic modifications; they show a tendency also to unite in molecular proportions to form double salts, as in dolomite and alstonite; in these cases the double salt is itself isomorphous with the group. But it is interesting to find that there is a second molecular compound of barium and calcium carbonates also represented by $BaCa(CO_3)_2$, which crystallises in the monoclinic system and cannot be referred to either group. This is the mineral **barytocalcite,** which is also found at Alston, and occurs in white translucent crystals represented in Fig. 617. The mineral in some respects resembles calcite, for there is a perfect cleavage parallel to *m* {110}, and a nearly perfect cleavage parallel to C {001}; the angles, C*m* (001) : (110) = 77° 6′, and *mm* (110) : ($1\bar{1}0$) = 73° 6′, are nearly equal to RR (100) : (010) = 74° 55′ of calcite; the acute negative bisectrix (with a very small axial angle) is nearly equally inclined to C (001), *m* (110), *m* ($1\bar{1}0$), so that under the microscope cleavage-fragments of this mineral may easily be mistaken for calcite.

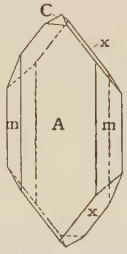


Fig. 617.—Barytocalcite, A {100}, *m* {110}, C {001}, *x* {$\bar{1}21$}.

The only substance which is definitely dimorphous and belongs to both groups is $CaCO_3$; the existence of a hexagonal modification of $BaCO_3$, $SrCO_3$, and $PbCO_3$ is inferred from their presence in certain varieties of calcite; while an orthorhombic variety of $ZnCO_3$ is indicated by the presence of Zn in aragonite and cerussite.

Among the fibrous and massive carbonates of lime, fibrous varieties, and such as do not show well-defined cleavage, have generally been referred to aragonite.

THE BASIC CARBONATES

Chessylite.—Basic carbonate of copper; $2CuCO_3 . Cu(OH)_2$; $CuO = 69{\cdot}3$, $CO_2 = 25{\cdot}5$, $H_2O = 5{\cdot}2$.

Monoclinic.

$$a : b : c = 0{\cdot}850 : 1 : 1{\cdot}760. \quad \beta = 87° 36'.$$

$$m = \{110\},\ C = \{001\},\ k = \{111\},\ l = \{013\}.$$

$mm\ (110) : (1\bar{1}0) = 80° 41'$, $kk\ (111) : (1\bar{1}1) = 73° 56'$, $Cm\ (001) : (110) = 88° 10'$,
$Ck\ (001) : (111) = 68° 12'$, $Cl\ (001) : (013) = 30° 24'$.

Cleavage {011}, fair. Brittle. Fracture, conchoidal. $H = 4$; $G = 3{\cdot}8$. Deep blue. Streak, smalt-blue. Lustre, vitreous. Translucent; $\gamma = 1{\cdot}838$, $\beta = 1{\cdot}758$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}108$. Axial plane perpendicular to (010). Acute bisectrix inclined at 77° 24′ to the normal of A and at 15° to the normal of C. $2E = 151°$; $\rho > v$. Easily fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Chessy** (near Lyons, France).

Malachite.—Basic carbonate of copper; $CuCO_3 . Cu(OH)_2$; $CuO = 72{\cdot}0$, $CO_2 = 19{\cdot}9$, $H_2O = 8{\cdot}1$.

Monoclinic.

$$a : b : c = 0{\cdot}881 : 1 : 0{\cdot}401. \quad \beta = 61° 50'.$$

$$m = \{110\},\ C = \{001\},\ A = \{100\}.$$

$$AC\ (100) : (001) = 61° 50',\ mm\ (110) : (1\bar{1}0) = 75° 40'.$$

Twinned on (100). Cleavage {010}, and {001}, perfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 4{\cdot}0$. Colour, emerald-green. Streak, verdigris-green. Lustre, sub-adamantine. Translucent; $\beta = 1{\cdot}875$, $\alpha = 1{\cdot}655$. Birefringence, very strong, negative; $\gamma - \alpha = 0{\cdot}254$. Axial plane (010). Acute bisectrix inclined at 66° 30′ to the normal of A, and at 4° 40′ to the normal of C. $2E = 89° 18'$; $\rho < v$. Easily fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Rheinbreitbach** (near Coblenz).

Chessylite and **Malachite.**—The two basic carbonates of copper are striking minerals on account of their colour. Chessylite (Germ. *Kupferlasur*, Fr. *azurite*) derives two of its names from its remarkable blue colour; the English name is derived from the place Chessy, near Lyons, where the copper mines have yielded the most beautiful crystals known (Figs. 618 and 619); these are very perfect and have lustrous faces. The mineral is only transparent when very thin. The earthy varieties are of a lighter smalt-blue than the crystals.

Malachite (named from μαλάχη, the Greek for a mallow) is rarely crystallised, but is mostly found (*e.g.* at Nizhni Tagil and Gumeschev in the Urals) as compact or curvilaminar, nodular, mamillary and botryoidal masses. These sometimes have a radial-fibrous structure. Fig. 620 is from a cut and polished specimen. Fibrous masses have a beautiful silky lustre. The best crystals are thin prisms found at Betzdorf in Westphalia and Dillenburg in Nassau; the former show the twinning very clearly.

Chessylite readily passes into malachite by loss of CO_2 and gain of water. Crystals from Chessy are sometimes transformed into malachite at one end, and the two minerals are almost invariably associated together.

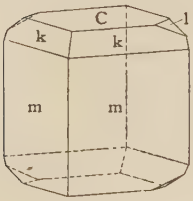


Fig. 618.—Chessylite, *m* {110}, C {001}, *k* {111}, *l* {013}.

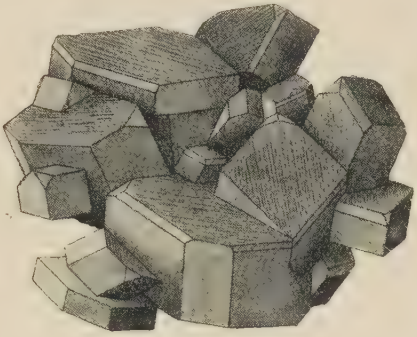


Fig. 619.—Chessylite from Chessy.

Malachite especially is a common decomposition product of various copper ores, and the presence of copper minerals is generally indicated by blue and green decomposition products.

At Chessy, in addition to the crystals of Fig. 619, are found spherical

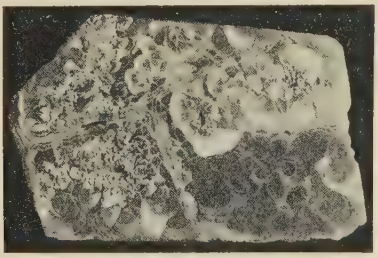


Fig. 620.—Malachite from the Urals.

concretions of chessylite, mostly about the size of a walnut, which consist of small crystals.

Near Clifton in Arizona stalactitic groups occur which consist of alternating concentric layers of malachite and chessylite.

Most of the malachite used for decorative purposes has been brought from the Urals, especially from the copper mines of Nizhni Tagil, where enormous quantities have been found. A mass in the School of Mines at Petrograd weighs 90 poods (=3247 lbs.).

SECTION XV

SILICATES OF DIVALENT METALS

THE FERRO-MAGNESIAN SILICATES

THE OLIVINE GROUP

			a : *b* : *c*
Forsterite	Mg_2SiO_4		0·4648 : 1 : 0·5857
Olivine	$(Mg,Fe)_2SiO_4$		0·4657 : 1 : 0·5865
Fayalite	Fe_2SiO_4		0·4584 : 1 : 0·5793
Tephroite	Mn_2SiO_4		0·4600 : 1 : 0·5938

Olivine.—Silicate of magnesium and iron; $(Mg,Fe)_2SiO_4$; for Mg_2SiO_4 (forsterite), MgO = 57·3, SiO_2 = 42·7; for Fe_2SiO_4 (fayalite), FeO = 70·5, SiO_2 = 29·5; for $9Mg_2SiO_4 + Fe_2SiO_4$ (chrysolite), MgO = 49·3, FeO = 9·8, SiO_2 = 40·9.

Orthorhombic.

$$a : b : c = 0·466 : 1 : 0·586.$$

A = {100}, B = {010}, C = {001}, *m* = {110}, *s* = {120}, *d* = {101}, *e* = {111}, *k* = {021}.

mm (110) : $(1\bar{1}0)$ = 49° 57′, *Ad* (100) : (101) = 38° 27′, *de* (101) : (111) = 20° 2′, *ss* (120) : $(1\bar{2}0)$ = 85° 57′.

Cleavage {010}, {100}, imperfect. Brittle. Fracture, conchoidal. H = 7; G = 3·4. Yellowish-green. Streak, colourless. Lustre, vitreous. Transparent; $\gamma = 1·697$, $\beta = 1·678$. Birefringence, positive; $\gamma - \alpha = 0·036$. Axial plane (001). Acute bisectrix perpendicular to A (100). $2V = 89°$. Dispersion, slight; $\rho < v$. Infusible. Decomposed by hydrochloric acid, leaving gelatinous silica.

With the above description compare crystals (chrysolite) from the **Red Sea.**

Forsterite occurs in colourless and yellow crystals, or in granular crystalline aggregates, with spinel in the volcanic ejections of Monte Somma (Mount Vesuvius).

Fayalite, or iron-olivine, is one of the commonest crystalline products of iron slags, in which it appears as tabular rhombs (combinations of B, *k*, and *m*), black and opaque, but possessing a typical vitreous lustre. It is also found in small crystals in the rhyolite of the Yellowstone National Park (Wyoming), and in nodules in the granite of the Mourne Mountains in Ireland. The name fayalite was originally given to a substance from Fayal Island in the Azores, which may, however, be only an iron slag originally brought to that coast as ship's ballast.

Tephroite is found as a grey cleavable mineral, together with zincite, willemite, and franklinite at Franklin (New Jersey), and with rhodonite and other manganiferous minerals at Pajsberg in Sweden. It was named from its colour (τεφρός, ash-coloured).

Numerous mixtures of these compounds with each other, and with the analogous calcium compound, which is not found as a distinct mineral, constitute the remainder of the olivine group. Among these the best defined is **monticellite,** $MgCaSiO_4$, a very rare mineral found in yellowish crystals at Mount Vesuvius, which may be a double salt, since the analysis corresponds to one molecule of forsterite united with one of Ca_2SiO_4.

The name **olivine** is generally used to include the mixtures having the composition $n(Mg_2SiO_4 + Fe_2SiO_4$ where n varies from 12 to 3.

In all these minerals the axial plane is (001) and the optic axes emerge nearly normal to the faces s, the angle 2V being about 89° in olivine.

Green crystals with a yellow metallic surface, due to alteration, found in the limburgite of the Kaiserstuhl near Freiburg in Baden, are distinguished by the name "hyalosiderite"; in these $n = 2$ and the crystalline form is slightly different: mm (110) : $(1\bar{1}0) = 50°\ 10'$, instead of 49° 57'; this may be another double salt.

Some olivine is titaniferous, owing probably to intermixture with an isomorphous titanate.

Olivine is but rarely found crystallised on a large scale, but in some of the more basic eruptive rocks (basalts, etc.) well-defined small crystals are very common, and may be recognised by their typical form in microscopic sections; this, with the high refractive index, strong double refraction, large axial angle, very imperfect cleavage, and tendency to alteration round the edges and along cracks, serves to identify the mineral, and distinguish it from augite. In consequence of these characters, sections of olivine present a high relief, like garnet and sphene, and polarise in bright colours of the second order.

In rock-specimens olivine is generally discernible by the eye as greenish to brownish glassy blebs and grains.

Olivine is an essential constituent of very many of the basic and ultra-basic rocks, and is, in fact, one of their most characteristic minerals.

In the rocks of granitic texture (olivine-gabbros, olivine-norites, peridotites, etc.) it usually occurs in crystalline grains; in those of trachytic texture (dolerites, basalts, etc.) it usually presents very symmetrical crystals of elongated hexagonal section. In these rocks it has always been one of the earliest minerals to crystallise. Large greenish patches of olivine are conspicuous in many basalts, *e.g.* that of Unkel in Rhenish Prussia, and in some of the Vesuvian lavas.

Among the ultra-basic rocks it is sometimes the predominant mineral, and associated with diallage or bronzite may constitute an "olivine-rock"; at Dun Mountain (New Zealand), it occurs in such quantity, associated with chromite alone, that it constitutes a rock mass, which is known by the name of "dunite." In the basic rocks it is usually associated with other ferro-magnesian minerals. Olivine is also found in certain talc-schists

and in the granular limestones associated with the crystalline schists ; it is also one of the important constituents of meteorites.

Twinning, on (011) or (012), is very rare, and is almost confined to the microscopic crystals found in rock sections.

Olivine gelatinises with acids, the most ferriferous varieties yielding most easily ; these are also the most fusible.

Olivine is particularly liable to suffer alteration into serpentine, a massive magnesian silicate, $H_4Mg_3Si_2O_9$ (p. 496), and most serpentine has been derived from the decomposition of olivine-rocks.

At Snarum in Norway, in the serpentine, have been found the large greenish crystals represented in Fig. 621. These consist almost entirely of pure serpentine, and when first discovered were supposed to be crystals of that mineral. But they have the same form as the olivine from Vesuvius,

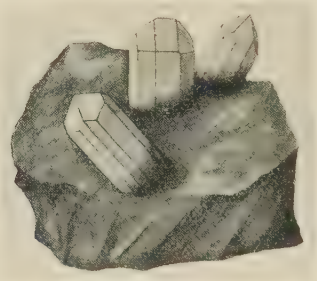


Fig. 621.—Olivine (serpentinised) from Snarum (Norway).

though on a larger scale, and sometimes contain a kernel of unaltered olivine, so that their derivation from that mineral is placed beyond doubt. Olivine can usually be recognised in rock sections by its partial decomposition into serpentine ; owing to its brittleness and the absence of well-defined cleavage it is usually traversed by irregular cracks, and the incipient decomposition proceeds along these cracks and fills them with green serpentine or brown ferric hydrates.

Chrysolite, an old classical name, which in Pliny refers probably to topaz, is now usually restricted to the clear yellow or green crystals of olivine brought from the East for use in jewellery. The locality of these is unknown, but they are said to come from the Red Sea. They are tabular crystals, owing to the predominance of A {100}, which is vertically striated ; the so-called chrysolite from Brazil and Ceylon is mostly chrysoberyl.

Olive-green and bottle-green crystals of olivine are also used in jewellery, and are generally known as " peridot," an old name for the mineral.

SECTION XVI

SILICATES OF DIVALENT METALS

THE FERRO-MAGNESIAN SILICATES (*Continued*)

THE PYROXENE GROUP

The name pyroxene was originally given by Haüy to certain greenish crystals found in the lavas of Vesuvius, Etna, and Auvergne, and also at Arendal in Norway. He mentioned as their essential feature a cleavage of about 88°, and gave the name, " stranger to fire " (from πῦρ and ξένος) as an indication of his opinion that they were only accidentally caught up in the lavas which contain them. The name is a misnomer, for pyroxene is one of the most characteristic minerals of a large group of basic igneous rocks. Many minerals which have been described under different names and as of very different composition have been referred to pyroxene, and the name is now conveniently used for a whole group. The old names are still used to distinguish the various members of the group.

The pyroxene group includes minerals which possess a ready cleavage of about 87°, and, except when they contain alumina, can be referred to the type $R''SiO_3$; they form a well-defined group of minerals passing into each other by a series of intermediate isomorphous mixtures; they include minerals belonging to no less than three different systems.

MONOCLINIC PYROXENES

Diopside.—$CaMg(SiO_3)_2$; $CaO = 25{\cdot}9$, $MgO = 18{\cdot}6$, $SiO_2 = 55{\cdot}5$. Monoclinic; symmetry, planar (?).

$$a : b : c = 1{\cdot}0921 : 1 : 0{\cdot}5893. \quad \beta = 74° 10'.$$

$m = \{110\}$, $A = \{100\}$, $B = \{010\}$, $C = \{001\}$, $u = \{111\}$, $p = \{10\bar{1}\}$, $s = \{11\bar{1}\}$, $o = \{22\bar{1}\}$.

mm $(110) : (1\bar{1}0) = 92° 50'$, AC $(100) : (001) = 74° 10'$, uu $(111) : (1\bar{1}1) = 48° 29'$, ss $(\bar{1}11) : (\bar{1}\bar{1}1) = 59° 11'$, Cp $(00\bar{1}) : (10\bar{1}) = 31° 20'$, Cu $(001) : (111) = 33° 49'$, Cm $(001) : (110) = 79° 9'$, mo $(110) : (22\bar{1}) = 35° 30'$, ms $(110) : (11\bar{1}) = 58° 49'$.

Twinned on (100). Cleavage {110}, fair; sometimes (001) (parting). Brittle. Fracture, conchoidal. $H = 5\frac{1}{2}$; $G = 3{\cdot}3$. Light green. Streak, white. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}703$, $\beta = 1{\cdot}681$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}030$. Axial plane (010); acute bisectrix inclined at 53° 55′ to the

normal of A and 20° 15′ to the normal of C. $2E = 111°$; $\rho > v$. Fusible (3 to 4). Insoluble in acids.

With the above description compare crystals from **Ala** (Piedmont) (Fig. 622).

Augite contains Al_2O_3 and Fe_2O_3 in addition to the constituents of diopside. Common form : A {100}, *m* {110}, B {010}, *s* {11$\bar{1}$}. Colour, black. Otherwise, characters nearly the same as those of diopside.

With this description compare crystals from **Schima** in Bohemia (Fig. 625).

Diopside.—The character of a typical pyroxene may best be studied in the clear green crystals of diopside which are found, with crystallised garnet, in a mass of garnet-rock in the Ala valley in Piedmont (Fig. 629).

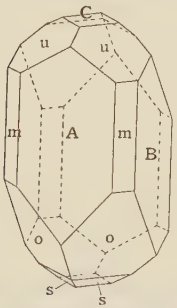


Fig. 622.—Diopside, A {100}, *m* {110}, B {010}, C {001}, *u* {111}, *o* {22$\bar{1}$}, *s* (11$\bar{1}$}.

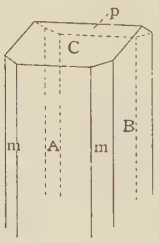


Fig. 623.—Diopside from Nordmark, A {100}, *m* {110}, B {010}, C {001}, *p* {$\bar{1}$01}.

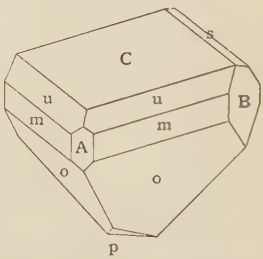


Fig. 624.—Diopside from New York, A {100}, *m* {110}, B {010}, C {001}, *u* {111}, *s* {$\bar{1}$11}, *o* {22$\bar{1}$}, *p* {10$\bar{1}$}.

They are generally a combination of B {010}, A {100}, *m* {110}, *u* {111}, *o* {22$\bar{1}$}, C {001}, of the habit shown in Fig. 622. The face C is quite dull. The pale green crystals are often of a darker green at one end, and this

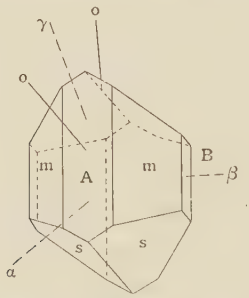


Fig. 625.—Augite, A {100}, *m* {110}, B {010}, *s* {11$\bar{1}$}.

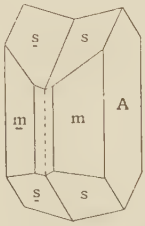


Fig. 626.—Augite twinned on (100).

seems to be accompanied by the development of certain faces at that end, as though the crystals might be differently terminated at the two ends (Class III, p. 91). Crystals possessing only a plane and not an axis of symmetry have, in fact, been found in Orange Co. (New York), terminated at one end by {001}, {111}, {$\bar{1}$11}, and at the other by {22$\bar{1}$}, {10$\bar{1}$} (Fig. 624).

Twinning on A is common ; either two individuals are united by this face (*cf.* Fig. 626), or a crystal is traversed by twin-lamellæ parallel to it. There are sometimes also twin-lamellæ parallel to C {001}.

The following is an analysis of a colourless crystal from Ala :

SiO_2	CaO	MgO	FeO
54·74	26·03	17·02	2·91

indicating a nearly pure silicate of lime and magnesia, with only a slight replacement of the latter constituent by ferrous oxide. The extinction-angle on B ($=c\gamma$) is here 36° 5′.

A colourless diopside from Nordmark in Sweden, which is nearly identical with the Ala mineral in composition, gave an extinction of 38° 3′. The extinction-angle of a pure diopside (free from iron) prepared artificially was found to be $38\frac{1}{2}°$.

Other pyroxenes which, as being mainly lime-magnesia silicates, may be termed diopside, contain a much larger proportion of iron, and sometimes also manganese, and the change in composition is accompanied by a change of physical characters.

The following observations were made by Doelter (A) on a dark green pyroxene from Nordmark, and (B) on a dark-coloured massive pyroxene from Tunaberg in Sweden, to which the name **hedenbergite** (after the Swedish chemist Hedenberg) was given by Berzelius before the mineral was known to belong to the pyroxene family.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Extinction $c\gamma$
(A)	50·91	0·17	0·76	17·34	22·93	7·21	+46° 45′
(B)	47·62	1·88	0·10	26·29	21·53	2·76	+47° 50′

Here an increase in the percentage of iron seems to involve an increase in the extinction-angle ; other observations have supported this conclusion.

In the above two analyses a new feature is introduced, for small percentages of the sesquioxides begin to make their appearance ; it is, in fact, found that very many pyroxenes contain varying proportions of alumina and ferric oxide, which may even rise to as much as 20 per cent. Rammelsberg, in 1858, urged the necessity of distinguishing between the ferrous and ferric oxide in the analysis of pyroxenes, and the analyses subsequent to that date enable us now to divide the monoclinic pyroxenes into two classes : (1) diopsides, or pyroxenes containing no sesquioxides, and (2) augites, or pyroxenes in which sesquioxides are present.

Many diopsides can be represented as a combination of one molecule $CaSiO_3$ with one molecule $MgSiO_3$ in which Mg may be partly replaced by Fe″ ; but a consideration of the ferriferous diopsides led Wülfing to the conclusion that the members of this series are to be regarded as isomorphous mixtures, in varying proportions, of the silicates $CaMgSi_2O_6$, $CaFeSi_2O_6$, and $MgFeSi_2O_6$. The first of these is the diopside proper from Ala ; the second is the mineral referred to above as hedenbergite ; the third is not known among the monoclinic pyroxenes as a distinct mineral, neither are the corresponding manganese compounds.

In the manganiferous diopsides (sometimes distinguished by the name schefferite) an increase of manganese acts like the increase of iron and makes the extinction-angle ($c\gamma$) larger. Flink found this angle to be as much as 69° for a ferriferous schefferite from Långban in Sweden.

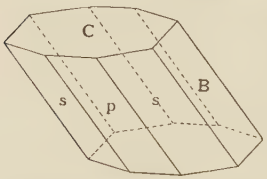


Fig. 627.—Schefferite, B {010}, C {001}, p {10$\bar{1}$}, s {11$\bar{1}$}.

Augite, a word borrowed from Pliny, was a name used before pyroxene and applied to the dark opaque crystals found in many basaltic lavas; these were distinguished from tourmaline and hornblende and recognised as a separate species by Werner about 1792.

Typical augite occurs as black porphyritic crystals in basalt and basaltic rocks in many parts of the world; in addition to the constituents of diopside it contains a considerable proportion both of alumina and of ferric oxide; the habit is usually that of Fig. 625, and the crystals are often twinned on A (100), as in Fig. 626. When the basalt decomposes into a clayey material the augite is left as separate crystals, and such specimens are to be found in all mineral collections; such are the crystals from Bilin and other Bohemian localities, and those from Mount Bufaure in the Fassathal (Tyrol). The latter, which are found as porphyritic constituents of an altered melaphyre, have curved faces of n {$\bar{1}$02}, which in the twinned crystals form a rounded termination to one end of the twin.

These black basaltic augites closely resemble the basaltic hornblendes in colour and appearance, but may be distinguished from them by the nearly rectangular cleavage. In thin fragments or sections they are brown and transparent, and the mineral is easily recognised in microscopic sections by its high relief, brown colour, and the cleavage-cracks. It will be seen from Fig. 625 that in augite, as in diopside (see p. 186), one optic axis emerges nearly normal through the basal plane C, and the other obliquely through the ortho-pinakoid A. Hence sections perpendicular to the prism m will exhibit a series of nearly rectangular cleavage-cracks (Fig. 628), whose angles are bisected by the extinction-directions,[1] and viewed in convergent light they show an optic axis nearly central; sections parallel to A give parallel cleavage-cracks, straight extinction, and an optic axis near the edge of the field of view. If the latter sections are from a twin-crystal and so consist of two overlapping plates, then in the extinction-position each plate will contribute an optic axis, and the interference-figure may be mistaken for that of a biaxial crystal cut perpendicular to the acute bisectrix; if it be viewed by monochromatic light, the form of the rings in the diagonal position will at once show it to be a composite figure.

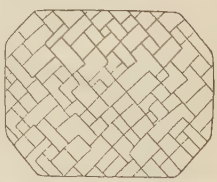


Fig. 628.—Augite, section perpendicular to the prism-zone.

[1] Owing to the fact that such sections are nearly perpendicular to an optic axis, the extinction-directions vary considerably with a slight difference in the direction of the section; so that sections not quite perpendicular to the prism may show unsymmetrical extinction. Similarly, the extinction on sections not quite parallel to A may not be straight.

Another variety of augite, in which the sesquioxide is mainly alumina, is green in colour and is known as "fassaite," after the Fassathal in the Tyrol, where it occurs at the contact of augite-syenite with a limestone. The crystals show the prism $m\{110\}$ terminated by steep faces of $o\{\bar{2}21\}$ with $s\{\bar{1}11\}$.

As in the diopsides, so also in the augite series, the optical characters change with the composition; the extinction-angle on the clino-pinakoid B varies from about 37° to 50°; generally speaking, it seems to increase with the percentage of iron.

There has long been doubt as to what is the aluminous silicate isomorphous with diopside which enters into the composition of the augite group; most of the analyses are explainable (following the suggestion of Tschermak) as isomorphous mixtures of the diopside and hedenbergite molecules, $CaMgSi_2O_6$ and $CaFe''Si_2O_6$, with an alumo-silicate $R''Al_2SiO_6$ (or $R''Fe''_2SiO_6$), where $R''' = (Ca, Mg, Fe'')$. Some pyroxenes, however, contain less silica in proportion to the R''O than would be required for these formulæ, and others more.

According to Zambonini any of these pyroxenes can be represented empirically as a mixture of a diopside molecule $R''SiO_3$ with an aluminate molecule $R''(Al, Fe)_2O_4$ and a silicate of trivalent metals $R'''_2(SiO_3)_3$ or $R''R'''_2(SiO_3)_4$.

Some varieties contain alkali, from an admixture of the acmite molecule (p. 479).

The observations of Doelter show that if a curve be constructed with the extinction-angles for abscissæ and the percentages of ferrous oxide for ordinates, it is not a continuous curve; his analyses can, however, be expressed as mixtures in varying proportions of the diopside molecule with the silicates $CaFe''Si_2O_6$, $MgAl_2SiO_6$, $MgFe'''_2SiO_6$, and $Na_2Al_2SiO_6$, and if the sum of the last four be taken for the ordinates a continuous curve is obtained. It appears, therefore, that in the augite series the extinction-angle on B increases as the proportion of the silicate $CaMgSi_2O_6$ diminishes, and this was shown above to be also true of the diopside series.

The extinction-angle is a character easily measured, and useful for the purpose of distinguishing the mineral in cleavage fragments or sections. The extinction-angle on cleavage-flakes m will, in accordance with the diagram on p. 163, depend upon the optic axial angle 2V and the angle $c\gamma$. The latter may vary from 36° to 54° or occasionally more. The variation of the optical characters and of the specific gravity in the pyroxene group is illustrated in the following table by the minerals which have already been mentioned above.

	β	$\gamma - \alpha$	$2E_{Na}$	$c\gamma$	Spec. Grav.
Diopside, Ala . . .	1·680	0·030	111°	39°	3·30
Hedenbergite, Tunaberg	1·737	0·019	120°	47°	3·492
Augite, Bohemia . .	1·712	0·024	116°	46° 40′	

The pleochroism of the pyroxenes is extremely slight, and until recently one of the usual characters employed in distinguishing a pyroxene from an amphibole in rock sections was the pleochroism of the latter; but, in reality, coloured diopsides and augites frequently show a slight change of colour when rotated on the microscope stage above the polariser. Ægirite (p. 479) is strongly pleochroic.

In addition to the diopside from Ala and from New York, other specimens of monoclinic pyroxene occasionally show a difference of termination at the two ends of the prism, indicating that the mineral probably possesses only a plane of symmetry and not a digonal axis perpendicular to it; and therefore belongs to Class III of pp. 91-92. This has been confirmed by the etching figures produced on the prism-faces by hydrofluoric acid; the mineral is, however, usually holosymmetric in appearance.

The monoclinic pyroxenes frequently possess a lamellar structure parallel to C (001), due to twinning on that face; the varieties from Sala in Sweden, and from the Mussa-Alp in the Ala valley, possess a sort of cleavage parallel to A (100) and C (001); this is found to be in reality not a true cleavage, but a "parting" due to the fact that these planes are glide-planes and planes of secondary twinning; the parting only occurs at intervals and not at *any* point in the mass of the crystal, as would be the case with a true cleavage. These parting-faces have been the subject of much study, and are now supposed to be due to pressure. Massive specimens often exhibit this lamellar structure.

Some Noteworthy Localities:

Ala (Piedmont).—Clear green diopside of the habit of Fig. 622 (sometimes also resembling Fig. 623) occurs with crystallised red garnet and scaly chlorite, lining cavities in a mass of garnet rock which contains grains

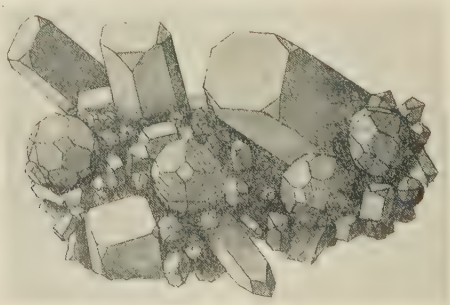


Fig. 629.—Diopside with Garnet, from Ala.

of diopside and chlorite, and traverses serpentine. The contrast between the pale green diopside, the rich red garnet, and dark green chlorite, makes this one of the most beautiful mineral associations to be found in collections. Fig. 629 is from a specimen in the British Museum.

Mount Vesuvius.—Some of the Vesuvian lavas contain porphyritic black crystals like Fig. 625. In the ejected blocks of **Monte Somma,** beautiful crystals, colourless, yellow, brown or black, are found lining

druses with sanidine, anorthite, leucite, nepheline, etc. Some of these are very rich in faces, and the habit may be that of Fig. 622 or Fig. 623.

Nordmark (Sweden).—Dark green or black crystals of considerable size, resembling Fig. 623, line cavities in the massive green granular pyroxene of the iron mines. With them are associated magnetite, chlorite, and sometimes blende.

Acmite, or ægirite, is a remarkable monoclinic member of the pyroxene group which may be described as diopside in which the two divalent atoms Ca Mg are replaced by a monovalent and a trivalent atom, Na′Fe‴. This mineral has the composition $NaFe'''(SiO_3)_2$, corresponding to

Na_2O	Fe_2O_3	SiO_2
13·4	34·6	52·0

The axial angle β is 73° 11′, instead of 74° 10′, as in diopside. Acmite differs also in its optical characters from diopside and augite. The birefringence is negative; $\beta = 1{\cdot}799$; $2E = 134\frac{1}{2}°$. The extinction-angle ($c\gamma$) on B is about 85°, so that $c\alpha$ is about 5°. Readily fusible (2).

The original acmite occurs in dark brown or green prisms, often bent and broken, in quartz, in pegmatitic veins of the granite of Eker in Norway; the form is shown in Fig. 630. It is characterised by steep pyramids, whence its name, from ἀκμή, a point; *o* is {$\bar{6}61$}. This figure is reversed in order to show the forms more clearly. Pleochroism slight: α light brown, β greenish yellow, γ brownish yellow.

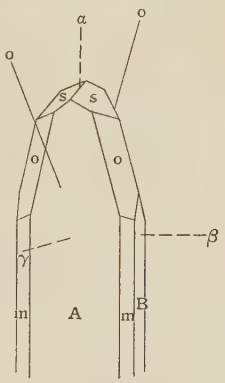


Fig. 630.—Acmite, A {$\bar{1}00$}, *m*{$\bar{1}10$}, B {$0\bar{1}0$}, *s*{$\bar{1}11$}, *o* {$\bar{6}61$}.

The name ægirite is given to the dark green variety which occurs in blunt-ended crystals as a constituent of the augite-syenites and elæolite-syenites of Norway; some of the rocks in the Oslo (Christiania) district consist mainly of ægirite and felspar, often with quartz and nepheline; and similar rocks are found in Abyssinia and Madagascar. The pleochroism of ægirite is strong: α grass green, β pale green, γ yellowish brown, and is very characteristic of the mineral. Extinction, $c\alpha = 3°$.

Spodumene is an alkali-pyroxene, $LiAl(SiO_3)_2$, corresponding in composition to acmite, but differing somewhat widely in form from the other pyroxenes: *mm* (110) : ($1\bar{1}0$) = 93° 0′; $\beta = 69°\ 40'$: it possesses not only a good prismatic cleavage, but an even better "parting" parallel to {100}. It is found in very large white crystals in the granite of Goshen (Massachusetts), and Branchville (Connecticut); but at both localities is much altered. Clear, transparent yellow crystals come from Brazil, and small crystals of a very beautiful green colour ("hiddenite") from Alexander County (North Carolina); one of the most beautiful facetted gems in the British Museum is cut from a clear crystal of the latter.

Another transparent variety, of lilac colour, which occurs in large crystals in California, is cut as a gem stone under the name "kunzite."

ORTHORHOMBIC PYROXENES

Enstatite.—Silicate of magnesium; $MgSiO_3$; MgO = 40·2, SiO_2 = 59·8; FeO usually replaces some of the MgO.

Orthorhombic.

$$a : b : c = 0{\cdot}970 : 1 : 0{\cdot}570.^1$$

$$mm\ (110) : (1\bar{1}0) = 88°\ 20'.$$

Cleavage {110}, {010}. Brittle. Fracture, uneven. H = 5½; G = 3·2. White. Streak, white. Lustre, vitreous. Translucent; $\beta = 1{\cdot}659$. Birefringence, weak, positive; $\gamma - \alpha = 0{\cdot}009$. Axial plane (010); acute bisectrix normal to (001). $2V = 70°$; $\rho < v$. Infusible. Insoluble in acids.

With the above description compare imperfect prisms from **Mount Zdjar** in Moravia.

The mineral from Mount Zdjar in Moravia was described by Kenngott under the name **enstatite** in 1855; it had previously been regarded as a scapolite; and he pointed out the close chemical relationship between this mineral, the augites, and two other minerals which had been known since the time of Haüy as hypersthene and bronzite; the latter were lamellar and fibrous minerals without definite crystalline form, and therefore difficult to place in the system. Hypersthene and bronzite only differ chemically from enstatite in containing more Fe replacing Mg. Des Cloizeaux showed from the optical characters that these three minerals are orthorhombic, and the timely discovery by von Lang (1869) of measurable crystals in a meteorite which fell at Breitenbach in Bohemia completed the determination of enstatite as a species. In the same year small tabular crystals found in a volcanic ejected block at Laach in Rhenish Prussia were described by vom Rath under the name "amblystegite," on account of their flat dome terminations (*ἀμβλύς*, obtuse; *στέγη*, a roof), and these were soon found to correspond in form with the enstatite of the meteorite and to be crystallised hypersthene.

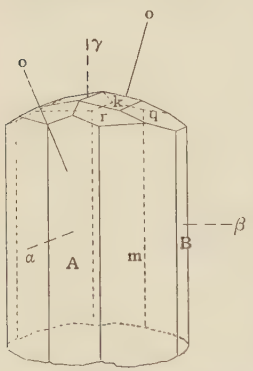


Fig. 631. Enstatite, A {100}, *m* {110}, B {010}, *k* {012}, *q* {023}, *r* {223}.

Subsequently (1874) enormous crystals (Fig. 631), found in the apatite-bearing schists of Bamle in Norway, were identified by Brögger and vom Rath as also enstatite. These observations established the existence of a group of rhombic pyroxenes.

They differ from the monoclinic pyroxenes in having straight extinction through both prism and (010), whereas an augite has an oblique extinction

[1] In accordance with the usual custom in the orthorhombic system enstatite is here placed with the obtuse angle of the cleavage-prism {110} in front. In order to be comparable with the monoclinic pyroxenes, in which the acute angle is in front (*cf.* p. 473), the axes *a* and *b* should be interchanged. The axial ratios would then be $a : b : c = 1{\cdot}031 : 1 : 0{\cdot}588$; the optic axial plane would be (100).

of 40° to 50° through (010) and of about 35° through (110); they have much weaker double refraction and exhibit a well-marked cleavage or parting parallel to {010}. Hypersthene is much more pleochroic than augite: α reddish brown, β yellowish brown, γ green. These characters serve to identify a rhombic pyroxene in sections of certain trachytes, andesites, etc., in which it occurs as an essential constituent of the rock.

Light green transparent fragments of enstatite, containing 5 per cent of FeO, which occur with the diamond in the " blue ground " of Kimberley, are sometimes cut as gem stones.

Hypersthene occurs in dark-brown masses, with bronzy lustre on cleavage surfaces, associated with labradorite, in a norite at St. Paul Island in Labrador.

ANORTHIC PYROXENES

Rhodonite.—Silicate of manganese; $MnSiO_3$; MnO = 54·1, SiO_2 = 45·9. Anorthic.

$$a : b : c = 1{\cdot}073 : 1 : 0{\cdot}621.$$

$$\alpha = 103° 18', \beta = 108° 44', \gamma = 81° 39'.$$

$$m = \{1\bar{1}0\}, M = \{1\bar{1}0\}, C = \{001\}, B = \{010\}, n = \{22\bar{1}\}, k = \{2\bar{2}\bar{1}\}.$$

$$m\text{M}\ (110) : (1\bar{1}0) = 87° 32', Cm\ (001) : (110) = 68° 45', \text{CM}\ (001) : (1\bar{1}0) = 86° 24'.$$

Cleavage {1$\bar{1}$0}, {110}, perfect; {001}, fair. Brittle. Fracture, uneven. H = 6; G = 3·6. Flesh-red. Streak, white. Lustre, vitreous. Translucent; β = 1·73. Birefringence, negative, weak; $\gamma - \alpha = 0{\cdot}010$. Axial plane inclined at 63° to M and 38° to C; acute bisectrix inclined at 51° 47′ to the normal of M and 51° 40′ to the normal of C. $2V = 76°$; $\rho < v$. Fusible ($2\frac{1}{2}$). Partly soluble in hydrochloric acid.

With the above description compare crystals from **Långban** in Sweden.

This mineral receives its name from the beautiful red colour (ῥόδον, a rose), and is used as an ornamental stone, especially in Russia, where it is quarried in large quantities in the Ural Mountains. It generally contains a considerable proportion of calcium and iron; the former is sometimes due to intermixed calcite, which may be detected by effervescence with acids; the iron may be due to an intermixture of the isomorphous ferrous silicate $FeSiO_3$.

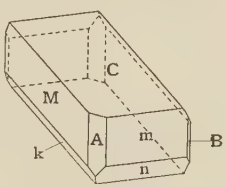


Fig. 632.—Rhodonite, A {100}, C {001}, m {110}, M {1$\bar{1}$0}, B {010}, n {22$\bar{1}$}, k {2$\bar{2}\bar{1}$}.

The rhodonite from the zinc mines of Sterling Hill (New Jersey), contains about 6 per cent of ZnO, and is known as "fowlerite"; it occurs (sometimes in large crystals) with franklinite in limestone.

Another anorthic pyroxene is **babingtonite** (Ca, Fe, Mn) $SiO_3 . Fe_2(SiO_3)_3$, which is found as small black crystals in Norway and at the Haytor Iron Mines in Devonshire, where it was formerly worked as an iron ore.

THE AMPHIBOLE GROUP

The minerals referred to this group are very similar in composition to the pyroxenes; some of them have indeed the same composition as hypersthene $(Fe,Mg)SiO_3$; and like the pyroxenes some of them contain alumina and ferric iron. But they differ from the pyroxenes in possessing a cleavage of about 56° instead of 87°. The name amphibole was introduced by Haüy (*ἀμφίβολος* = doubtful) to replace "schorl," an old mining term which was applied both to the black tourmaline and to hornblende; these two minerals resemble each other closely in form. Hornblende is also an old mining name. Haüy's name, amphibole, like pyroxene, may be conveniently retained for the whole group.

A resemblance has been noticed between some of the angles of the amphiboles and those of the pyroxenes. Thus, the cleavage-angle of hornblende (55° 49′) is nearly equal to the angle of the prism {210} of augite (55° 26′), while the angle β is nearly the same in both; but the difference in the cleavage shows that they are really distinct minerals.

This is also proved by a study of uralite, a mineral having the faces of augite and the cleavage of hornblende; this is clearly an alteration product—a pseudomorph of hornblende after augite. Further, the lime-magnesia silicate, tremolite, in the amphibole group, while conforming to the formula $R''SiO_3$, like the corresponding compound, diopside, in the pyroxene group, really has a different composition, for whereas diopside is $CaMg(SiO_3)_2$, tremolite is $CaMg_3(SiO_3)_4$.

Rose showed that when hornblende is fused, it re-crystallises as augite.

The amphibole group, then, contains minerals which possess a ready cleavage of about 56°, and, except when they contain alumina, can be referred to the type $R''SiO_3$. Like the pyroxenes, they form many isomorphous mixtures, and they belong to the same three systems.

MONOCLINIC AMPHIBOLES

Tremolite.—$CaMg_3(SiO_3)_4$; CaO = 13·4, MgO = 29·0, SiO_2 = 57·6. Actinolite contains also FeO, replacing MgO.

Monoclinic.

$$a : b : c = 0{\cdot}551 : 1 : 0{\cdot}294. \quad \beta = 73° 58'.$$

$m = \{110\}$, A = {100}, B = {010}, $r = \{011\}$, $p = \{10\bar{1}\}$, $e = \{130\}$, $t = \{101\}$.

mm (110) : $(1\bar{1}0) = 55° 49'$, rr (011) : $(0\bar{1}1) = 31° 32'$, pr $(10\bar{1})$: $(01\bar{1}) = 34° 25'$.

Twinned on A (100). Cleavage {110}, perfect; {100}, {010}, imperfect. Brittle. Fracture, uneven. H = 5½; G = 3·1. Pale green. Streak, grey. Lustre, vitreous. Translucent; $\beta = 1{\cdot}62$, $\alpha = 1{\cdot}60$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}028$. Axial plane (010); acute bisectrix inclined at 15° to normal of A (100), and almost parallel to the edge rr. 2V = 85°, $\rho < v$. Fusible (4). Insoluble in acids.

With the above description compare crystals from **Russell** (New York). Fig. 634 (*cf.* Fig. 633).

Hornblende contains Al_2O_3 and Fe_2O_3 in addition to the constituents of tremolite. Colour, black. Characters otherwise nearly the same as those of tremolite.

With the above description compare crystals from **Schima** (Bohemia), Fig. 633.

Tremolite and the other non-aluminous amphiboles corresponding to diopside are mostly columnar and fibrous crystals without definite terminations. The name tremolite was given in allusion to the Val Tremola (St. Gothard); the true tremolite, however, corresponding to the composition $CaMg_3(SiO_3)_4$, does not come from there but from Campolongo (Tessin), where it forms long white or greyish translucent blade-like prisms {110}, with vertical striations in the granular white or grey dolomite.

Green crystals found in limestone at Russell in New York are well terminated and have the forms shown in Fig. 634 ($e = \{130\}$, $t = \{101\}$). These, as well as green crystals from Gouverneur and brown crystals from Pierrepont, have nearly the composition given above for tremolite.

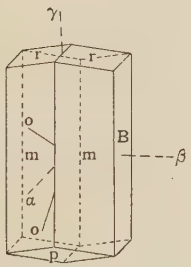


Fig. 633.—Hornblende, *m* {110}, B {010}, *r* {011}, *p* {10$\bar{1}$}.

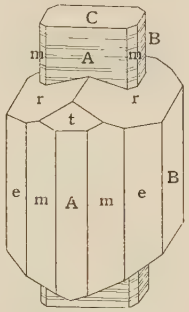


Fig. 634.—Amphibole enclosing parallel Pyroxene from New York, A {100}, B {010}, *m* {110}, *e* {130}, *t* {101}, *r* {011}, C {001}.

Fig. 634 also shows how the Russell crystals are intergrown in parallel position with pyroxene, the faces A and B being parallel in both. The basal plane C of the pyroxene is nearly parallel to the edge *rr* of the tremolite. For this reason *r* is here taken as {011}; though with many authors it has been the custom to place the amphiboles in the reverse position, and to make *r* {$\bar{1}$11}.

True tremolite is quite pale in colour; as the proportion of iron increases, the colour becomes a darker green; the name actinolite (Germ. *Strahlstein*) is given to the varieties which contain a considerable proportion of FeO, up to about 25 per cent. Actinolite is also markedly pleochroic, γ green, β yellowish green, α greenish yellow; the optical orientation and the refractive indices are practically the same as for tremolite. Actinolite is a very common mineral in the crystalline schists; it is usually found in columnar or fibrous aggregates.

A brown manganiferous tremolite from Långban in Sweden, known as **richterite,** contains about nine per cent of alkalis, of which two atoms are generally supposed to replace one atom of calcium.

Hornblende, the common black mineral corresponding to augite in the pyroxene group, contains alumina and generally ferric iron. It is a constituent of syenites and diorites, and of many crystalline schists. Amphibolite and hornblende-schist consist entirely of this mineral.

A pale green variety of hornblende, poor in iron, which occurs in calcite at Pargas in Finland, and corresponds in composition and mode of occurrence to fassaite among the pyroxenes, is distinguished as " pargasite."

The properties of hornblende are best studied in the variety known as basaltic hornblende, which occurs in black porphyritic crystals in some andesites, trachytes, and basalts ; it is these crystals, of the habit shown in Fig. 633, which were formerly confused with tourmaline, and known as schorl.

Excellent crystals are found weathered out of the altered basalts of Bilin and Schima in Bohemia, very similar in appearance to the augites from the same localities mentioned on p. 476. They are often twinned on (100), as in Fig. 635. The twin crystals may be easily recognised as

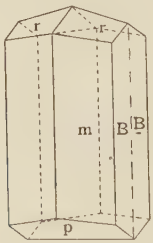


Fig. 635.—Hornblende twinned on (100).

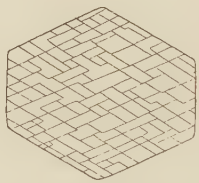


Fig. 636.—Hornblende, section perpendicular to the prism-zone.

terminated at one end by two faces (p), at the other by four faces (r), instead of by three at each end, as in Fig. 633. Lamellar twinning parallel to (001), like that of pyroxene, is very rare in amphibole.

These basaltic hornblendes are characterised by a very low extinction-angle on B (angle between γ and the edge Bm), which sinks to a few degrees, or even 0°, as compared with the usual angle for amphiboles (about 15°), and also by a very strong pleochroism, γ dark brown, α yellow ; but since these properties are acquired by ordinary hornblendes on heating, and in all the basaltic hornblendes the extinction-angle may be reduced to zero by heating in super-heated steam, it is possible that they are only due to alteration, and are acquired characters.

Under the microscope, cross sections of amphibole in rocks are easily recognised by the characteristic cleavage-cracks of Fig. 636 ; if the section is at right angles to the prism-zone, their angle is about 56°, and is bisected by the extinction-directions ; viewed in convergent light such sections show a positive obtuse bisectrix inclined at about 15° to the normal.

The composition of the aluminous amphiboles is still less certain than that of the aluminous pyroxenes. They cannot all be explained by importing the molecule $R''Al_2SiO_6$ which sufficed for most of the pyroxenes.

Scharizer found a variety from Jan Mayen Island, with about 27 per cent of sesquioxides, to have the composition $R''_3R'''_2Si_3O_{12}$; he gave to this the name "syntagmatite," previously used for the Vesuvian hornblende, which has a somewhat similar composition, and suggested that all the amphiboles may be regarded as isomorphous mixtures of the tremolite and syntagmatite molecules. Many of the amphiboles contain a small proportion of alkalis, and Tschermak regards them as mixtures of the tremolite molecule, $CaMg_3Si_4O_{12}$, with the molecules $CaMg_2Al_2Si_3O_{12}$ and $Na_2Al_2Si_4O_{12}$, Mg being partly replaced by Fe″, and Al by Fe‴.

Groth, following Zambonini, makes hornblende (like augite) a mixture of $CaMg_3(SiO_3)_4$ with $(Mg,Fe'')(Al,Fe''')_2O_4$ (in pargasite), with the addition, in black hornblende, of $(Fe''', Al)_2(SiO_3)_3$.

Some Noteworthy Localities :

The characteristic occurrences of **New York, Campolongo,** and **Bilin** have been mentioned above.

Vesuvius.—The sharp, brilliant, black crystals, called syntagmatite, occur with augite and mica, sometimes also idocrase and garnet, in cavities of the sanidine blocks of **Monte Somma.** They are rather flat prisms owing to the predominance of the *m* faces, and the absence of B, and are usually terminated like Fig. 633.

There are several rare alkali hornblendes comparable with acmite. **Arfvedsonite** is a soda-amphibole found in large black crystals in the elæolite-syenite of Kangerdluarsuk (Greenland), and in similar rocks elsewhere. It is strongly pleochroic. **Glaucophane** is a blue pleochroic mineral found in grains in certain mica-schists, gneisses, and phyllites; it has the composition $NaAlSi_2O_6 . (Mg,Fe,Ca)SiO_3$, corresponding to the union of a molecule of the acmite type with one of the enstatite type. **Riebeckite,** $2NaFe'''Si_2O_6 . Fe''SiO_3$, is another blue pleochroic amphibole of similar constitution found in granitic rocks in the island of Socotra and at Ailsa Craig in the Firth of Clyde.

ORTHORHOMBIC AMPHIBOLE

A mineral known as **anthophyllite** corresponds to enstatite and has the composition $(Mg,Fe)SiO_3$; the best specimens are found as brownish, fibrous, and flaky masses with hornblende, tremolite, and biotite, in a mica schist at Kongsberg in Norway. The pinakoidal cleavage {010} is less conspicuous in anthophyllite than in enstatite; the pleochroism is also less marked; the birefringence is greater, $\gamma - \alpha = 0{\cdot}024$.

ANORTHIC AMPHIBOLE

The only anorthic amphibole corresponding to rhodonite and babingtonite is a very rare mineral, known as **ænigmatite,** found in large black crystals in the elæolite-syenite of Julianehaab in Greenland. It possesses a cleavage of 65° 55′, and is a titano-silicate of sodium, iron, and aluminium.

GENERAL SURVEY OF THE PYROXENE AND AMPHIBOLE GROUPS

PYROXENE GROUP		AMPHIBOLE GROUP	
Orthorhombic		*Orthorhombic*	
Enstatite	$MgSiO_3$		
Hypersthene	$(Mg,Fe)SiO_3$	**Anthophyllite**	$(Mg,Fe)SiO_3$
Monoclinic		*Monoclinic*	
Diopside	$CaMg(SiO_3)_2$	**Tremolite**	$CaMg_3(SiO_3)_4$
Hedenbergite	$CaFe(SiO_3)_2$	**Actinolite**	$Ca(Mg,Fe)_3(SiO_3)_4$
		Richterite	$(Mg,Ca,Mn,K_2)SiO_3$
Augite	$Ca(Mg,Fe)Si_2O_6$ + $(Ca,Mg,Fe)(Al,Fe)_2SiO_6$	**Hornblende**	$Ca(Mg,Fe)_3Si_4O_{12}$ + $CaMg_2(Al,Fe)_2Si_3O_{12}$ + $NaAl(SiO_3)_2$
Acmite	$NaFe'''(SiO_3)_2$	**Riebeckite**	$NaFe'''(SiO_3)_2$ + $Fe''SiO_3$
Jadeite	$NaAl(SiO_3)_2$	**Glaucophane**	$NaAl(SiO_3)_2$ + $(Mg,Fe,Ca)SiO_3$
Spodumene	$LiAl(SiO_3)_2$		
Anorthic		*Anorthic*	
Rhodonite	$MnSiO_3$		
Babingtonite	$(Ca,Fe,Mn)SiO_3$ + $Fe'''_2(SiO_3)_3$	**Ænigmatite**	$(Fe'',Na_2)(Si,Ti)O_3$ + $Na(Al,Fe)(SiO_3)_2$

It has been shown above that these minerals form two parallel series crystallising in three systems.

The orthorhombic varieties are not very well defined; both enstatite and anthophyllite are liable to an internal decomposition, by which they acquire a pearly or submetallic lustre on the cleavage-surfaces, especially on B. The bronzy appearance caused by this change is probably due to very fine films of oxides or hydrates of iron forming in the cleavage-cracks, and is known as "schiller." The effect is particularly marked in the ferriferous varieties of enstatite known as "bronzite" (or "schillerspar"); this mineral is especially characteristic of gabbros and peridotites in which the olivine has often been serpentinised, or in the serpentines derived from such rocks; it was formerly supposed to be a distinct mineral, but is undoubtedly only an altered enstatite; the same change occurs equally in the more ferriferous varieties of $(Mg,Fe)SiO_3$, known as hypersthene. The original *Schillerspath* (or "bastite") from the Harz is so much altered that it practically has the composition of a serpentine. It has been shown by Judd that schillerisation is due to decomposition along solution-planes which are usually glide-planes.

The **hypersthene** of Labrador is of a dark pinchbeck-brown colour with a peculiar bronzy sheen, and the felspar (labradorite) with which it is associated shows brilliant opalescent colours. Among the monoclinic

series, **diallage** is a pyroxene which has suffered the same schillerisation, and closely resembles bronzite or hypersthene in appearance ; it has a platy parting parallel to A, and is often found interlaminated with bronzite, from which it is distinguished by the oblique extinction on B. Diallage is the usual pyroxene of gabbro. Among other varieties of pyroxene which deserve mention are two green minerals : " chrome-diopside," which contains a small percentage of Cr_2O_3 and is a conspicuous, though not common, constituent of the " blue ground " at Kimberley ; and " omphacite," which is a constituent of eclogite. Both of these may be recognised as pyroxenes by their cleavage and optical properties. A green variety of amphibole known as "smaragdite" corresponds to omphacite and is often found with it.

Amphibole shows a much greater tendency than pyroxene to appear in acicular, and even fibrous, crystals ; the most conspicuous example is the variety known as **asbestos,** which is so fibrous and flexible that it can be woven into cloth, and is very largely used as a non-combustible material for many purposes. In the mica-schist and talc-schist of Lombardy and Turin the best asbestos occurs in fine white silky fibres sometimes more than a yard in length ; a hair-like green asbestos sometimes accompanies the epidote on the fine specimens from the Untersulzbachthal. Inferior varieties of shorter and coarser fibre are worked at many other localities ; but now the greater part of what is used commercially as " asbestos " is really chrysotile, the fibrous variety of serpentine. " Mountain leather " and " mountain cork " are the names given to matted sheets or nodules of a yellow fibrous amphibole closely allied to asbestos ; all these have nearly the composition of tremolite or actinolite.

A blue fibrous mineral from Griqualand, known as " crocidolite," is probably a fibrous riebeckite ; by oxidation and partial replacement by silica it becomes converted into a hard, compact, golden-yellow material with fibrous structure and silky chatoyant lustre, much used for ornamental purposes and often called " cat's-eye " or " tiger-eye." This must be regarded as a pseudomorph of quartz after crocidolite.

Another variety of tremolite or actinolite of a totally different appearance is the compact mineral known as **nephrite** or jade. This has a hardness of about $6\frac{1}{2}$, and specific gravity about 3·0 ; it is one of the toughest of minerals, and has a splintery fracture. On account of its toughness and colour it has always been much prized in ancient times, and weapons and worked articles of jade have been found in many parts of the world. The ancient localities are not known, but it was probably always a rare mineral and found in isolated boulders ; it is much worked at the present time in India and China, and also in New Zealand and Alaska. Two varieties are known ; the white (which is especially prized in the East) has the composition of tremolite ; the green (" greenstone " of New Zealand, etc.) contains more FeO and is regarded as a compact actinolite.

A very similar mineral, generally confused with jade, and equally prized in the East, is the green or white **jadeite** ; this is a compact alkali-pyroxene, $NaAl(SiO_3)_2$, corresponding in composition to acmite and spodumene ; it is tough and has a splintery fracture like that of jade.

but is both denser and harder than jade, H = 7, G = 3·3, and it may be distinguished from jade by its readier fusibility, with yellow coloration of the flame. Like jade, the material worked has probably been derived from isolated boulders.

In many rocks pyroxene is altered into amphibole. The name "uralite" (from the original locality) has been given to such crystals, which have the form of pyroxene and the cleavage of amphibole, and the process is named uralitisation; it is exemplified by microscopic crystals in many diabases. Such a change can only take place by a reduction of the proportion of calcium in the pyroxene as compared with magnesium; it is therefore interesting to find that uralite is generally accompanied by calcite or epidote.

The parallelism of the pyroxenes and amphiboles is well shown by a comparison of their optical orientation, as illustrated by the annexed diagrams, Figs. 637, 638, which give the positions of the indicatrix-axes α and γ for several of them.

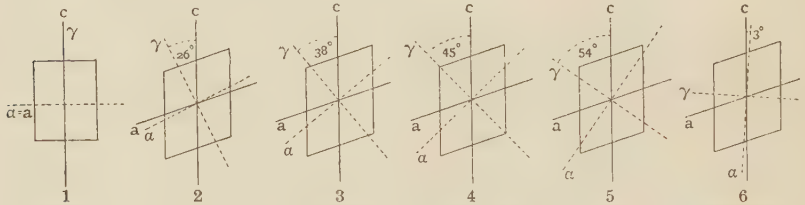


Fig. 637.—Optical Orientation in the Pyroxene Group.

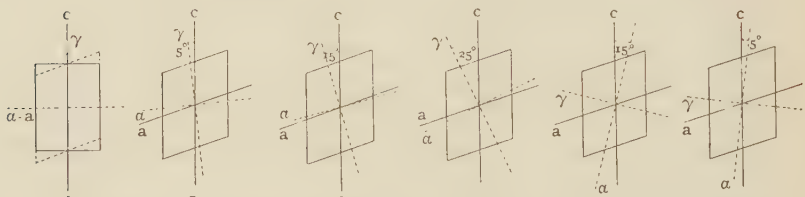


Fig. 638.—Optical Orientation in the Amphibole Group.

In each series there is a gradual rotation of the bisectrices in a counter-clockwise direction in passing from 1 to 6.

Two minerals of some importance are sometimes included in the pyroxene group, although they do not possess the characteristic cleavage, namely, wollastonite and pectolite. **Wollastonite** is found in white tabular crystals (Germ. *Tafelspath*) lining cavities in the ejected blocks of Monte Somma (Mount Vesuvius), associated with garnet, leucite, etc. It is monoclinic, tabular along {100}, and has a prism-angle of 92° 42′; but

[1] See footnote, p. 480.

differs from pyroxene in its cleavages; *viz.* two, perfect, A {100} and C {001} (AC = 84° 30′), also one, less perfect, parallel to {$\bar{1}$01}. The mineral is also found in many metamorphic limestones; it has the simple composition $CaSiO_3$.

Pectolite, $HNaCa_2(SiO_3)_3$, is a white mineral found in acicular crystals or fibrous masses of radiating structure, as a secondary product in cavities and veins of several basic rocks; it is monoclinic, and, like epidote, elongated along the axis *b*; its cleavages are the same as the principal cleavages, AC, of wollastonite, and it is readily fusible (2), and gives off water on heating.

By some authors pectolite is placed among the zeolites, which it certainly resembles in its mode of occurrence; others regard the water as of secondary origin, and suppose the original mineral to have conformed to the pyroxene formula as $(Na_2,Ca)SiO_3$. Compact pectolite is a very tough white material.

SECTION XVII

SILICATES (AND TITANATES) OF DIVALENT METALS (*Continued*)

THE PHENACITE GROUP

Dioptase . . .	H_2CuSiO_4
Phenacite . . .	Be_2SiO_4
Willemite . . .	Zn_2SiO_4

The minerals of this group are chiefly interesting as affording examples of the hexagonal-alternating symmetry-class, of which dioptase was chosen as the type (Fig. 193, p. 78).

Dioptase.—Silicate of copper; H_2CuSiO_4; $CuO = 50{\cdot}5$, $H_2O = 11{\cdot}4$, $SiO_2 = 38{\cdot}1$.

Hexagonal; symmetry, hexagonal alternating.

$$a = 94^\circ\ 58',\ [a : c = 1 : 1{\cdot}068].$$

$$R = \{100\},\ a = \{10\bar{1}\},\ s = \{70\bar{1}\}.$$

$$RR = (100) : (010) = 84^\circ\ 33',\ Rs = (100) : (70\bar{1}) = 8^\circ\ 12'.$$

Cleavage {110}, good. Brittle. Fracture, conchoidal. H = 5; G = 3·3. Emerald-green. Streak, green. Lustre, vitreous. Transparent; $\omega = 1{\cdot}667$. Birefringence, strong, positive; $\epsilon - \omega = -0{\cdot}056$. Infusible. Decomposed with gelatinisation by hydrochloric acid.

With the above description compare crystals from the **Khirgis Steppes** (Siberia), Fig. 193, p. 78.

Dioptase is a rare mineral, which first attracted attention in 1785 on account of its resemblance to emerald, for which it was then mistaken. It was made a distinct species by Haüy on account of the hardness, specific gravity, cleavage, and large proportion of copper. He gave it the name dioptase in allusion to the internal glitter which these green translucent crystals exhibit owing to their rhombohedral cleavage-cracks (διά, ὀπτάζω = I see through). By most authors the cleavage-rhombohedron {110}, of 54° 5′, which truncates the edges of R, is taken as {100}; R then becomes $\{11\bar{1}\}$ (*cf.* Fig. 183). The symmetry is made clear not only by the occurrence of the faces *s* (Fig. 193) on the alternate edges alone of the rhombohedron R, but by the striations on the latter; these are parallel to the edge R*s*, and the faces are also curved in this direction; in fact *s* of Fig. 193 is generally a curved surface ranging from (11.0.$\bar{1}$) to (30$\bar{1}$).

Dioptase was originally found in beautiful emerald-green crystals and groups lining cavities of a compact limestone, and sometimes accompanied by a little malachite, at Mount Altyn Tübe in the Khirgis Steppes. In 1890 precisely similar crystals, accompanied by chrysocolla and quartz, were brought to Europe from the Mindouli mine in the French Congo.

Since the mineral does not lose weight when heated to 350°, and water is only given off at a red heat, it is regarded not as a hydrated metasilicate but an acid orthosilicate H_2CuSiO_4, and is referred to the same group as phenacite and willemite ; these minerals exhibit the same symmetry, and phenacite has an imperfect rhombohedral cleavage ; but their prominent cleavage is the prism. The rhombohedron angles are :

Phenacite	63° 24′
Willemite	64° 30′
Dioptase	54° 5′ (cleavage).

Thus, dioptase is far less closely related to them than they are to each other.

Phenacite occurs in good, isolated, colourless crystals of habit somewhat similar to that of dioptase, on the amazon-stone of Pike's Peak, and at Mount Antero (Colorado), and has been found in crystals of considerable size in the emerald mines of the Urals, at Framont in the Vosges, and more recently in Brazil. These are sometimes interpenetration-twins twinned about the vertical axis. The mineral was named phenacite (*φένα*ξ, a deceiver) on account of its resemblance to quartz ; but it possesses a higher refringence and birefringence, $\omega = 1{\cdot}654$, $\epsilon - \omega = 0{\cdot}016$. When sufficiently clear it is occasionally cut as a gem stone.

Willemite has been mentioned already as a zinc ore which accompanies zincite and franklinite at the zinc mines of Franklin Furnace and Sterling Hill in New Jersey, where it occurs mostly as dull, pale yellow cleavable masses ; the cleavage is parallel to the base and the hexagonal prism. Crystals are comparatively rare ; large flesh-red crystals which owe their colour to a proportion (5 to 12 per cent) of MnO are known as " troostite."

ILMENITE

Ilmenite, $FeTiO_3$ (Germ. *Titaneisen*, Fr. *fer titané*), is an iron-black mineral closely resembling hæmatite in form and habit (*rr* (100) : (010) = 94° 29′ in ilmenite, and 94° 0′ in hæmatite) ; and it has a similar conchoidal fracture and submetallic lustre ; H = 5½, G = 4·8. Well-formed or bright crystals are rare ; they differ from hæmatite in their symmetry, which is that of the dioptase class, hexagonal alternating.

Ilmenite was formerly regarded as an isomorphous mixture of Fe_2O_3 and Ti_2O_3, *i.e.* as a titaniferous hæmatite $(Fe,Ti)_2O_3$, and was classed among the oxides as a member of the corundum group (*cf.* p. 409). It is distinguished from hæmatite by a slight but pronounced magnetism (it is, however, not polar like magnetite), and by the presence of titanium and of ferrous iron. It varies widely in composition (TiO_2 = 4 to 52, Fe_2O_3 = 1 to 60, FeO = 3 to

46 per cent), passing gradually into titaniferous hæmatite on the one hand, and on the other into nearly pure $Fe''TiO_3$ ($FeO = 47{\cdot}3$, $TiO_2 = 52{\cdot}7$), which has been found in steep rhombohedral crystals (" crichtonite ") in the Dauphiné.

Some varieties contain magnesia as well as ferrous oxide, and in these the ratio $(Mg,Fe)O : TiO_2$ is usually 1 : 1, so that they must be regarded as isomorphous mixtures of $FeTiO_3$ with $MgTiO_3$. Nearly pure $MgTiO_3$ occurs in Ceylon as a massive mineral with rhombohedral cleavage (geikielite), and a rare mineral, $MnTiO_3$, from Sweden, known as pyrophanite, is also isomorphous with ilmenite. The Fe_2O_3 may be due to an " isomorphous " admixture of hæmatite with $R''TiO_3$, since most varieties of ilmenite may be represented by the formula $m\,(Fe,Mg,Mn)TiO_3 + n\,Fe_2O_3$, as suggested by Rammelsberg. The original ilmenite from the Ilmen mountains in Russia is apparently a homogeneous mixture of this kind. It has recently been found, however, by Lacroix, that some specimens of ilmenite from Madagascar and from Maine, consist of a fine lamellar intergrowth of hæmatite and crichtonite like the perthitic intergrowths of felspars. Similar regular intergrowths of crichtonite and magnetite have also been found in Madagascar.

Platy crystals of ilmenite with triangular striation on the basal planes are common in diabase, and the mineral is a frequent constituent of the more basic rocks. Some of the black heavy sands derived from the decomposition of these rocks consist largely of grains of ilmenite.

TITANITE

Titanite.—Silicate and titanate of calcium; $CaSiTiO_5$; $CaO = 28{\cdot}6$, $TiO_2 = 40{\cdot}8$, $SiO_2 = 30{\cdot}6$.

Monoclinic.

$$a : b : c = 0{\cdot}755 : 1 : 0{\cdot}854. \quad \beta = 60°\ 17'.$$

$$A = \{100\},\ C = \{001\},\ x = \{102\},\ l = \{\bar{1}12\},\ n = \{111\},\ m = \{110\}.$$

$$ll\ (\bar{1}12) : (\bar{1}\bar{1}2) = 46°\ 7',\ Cx\ (001) : (102) = 21°\ 0',\ nn\ (111) : (1\bar{1}1) = 43°\ 49',$$
$$Cl\ (001) : (\bar{1}12) = 40°\ 34'.$$

Twinned on A (100). Cleavage {110}, {$\bar{1}$12}, {100}, imperfect. Brittle. Fracture, sub-conchoidal. H = 5; G = 3·5. Colour, greenish yellow. Streak, white. Lustre, adamantine. Transparent; refraction very strong; $\gamma = 2{\cdot}053$, $\beta = 1{\cdot}921$. Birefringence, very strong, positive; $\gamma - \alpha = 0{\cdot}140$. Axial plane (010). Acute bisectrix nearly normal to x (102). $2E_{Na} = 45°\ 40'$. Dispersion of optic axes very strong; $\rho > v$; $2E_{Li} = 51°$; $2E_{Tl} = 40°$ about. Fusible (3). Decomposed by hot hydrochloric acid.

With the above description compare crystals from **Zillerthal** (Tyrol).

Titanite, or sphene, is a common constituent of many igneous rocks, and is therefore of petrographical importance, although it only occurs sparingly and in small crystals; the large crystals to be seen in collections are found in gneiss, in chloritic schists, or in crystalline limestones. The crystals are usually angular in appearance (hence the name from $\sigma\phi\acute{\eta}\nu$, a wedge).

The habit is extremely variable, and the combination here figured is only one of many; different authors place the crystallographic axes in different positions. Fig. 639 is turned so as to correspond to the upper part of the large twinned crystal in Fig. 640; such twins are very characteristic. A (100) is the twin-plane and the individuals are sometimes juxtaposed, as in Fig. 640, but sometimes interpenetrant; they may then give rise to cruciform groups where such forms as s {021} or n {111} are predominant. A parting parallel to {221} appears to be due to lamellar twinning on that face, and the crystals are striated parallel to the same plane. The striations on l {$\bar{1}$12}, which are parallel to its intersections with C, and those on A (parallel to the edge Am) sometimes help one to recognise the forms on this complicated mineral.

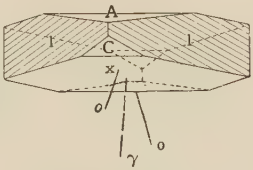


Fig. 639.—Titanite, C {001}, x {102}, A {100}, l {$\bar{1}$12}.

Titanite is most easily recognised by its strong axial dispersion, which in ordinary sections converts the hyperbola into fringes of red and blue light, and its apices into patches of white light; in rock sections the mineral is recognised by this feature and by its high relief; the birefringence is very strong. The dispersive power is very marked; $\beta = 1{\cdot}912$ for lithium light, and 1·932 for thallium light. This, and the high refractive index, would render it a valuable gem stone if the hardness were greater;

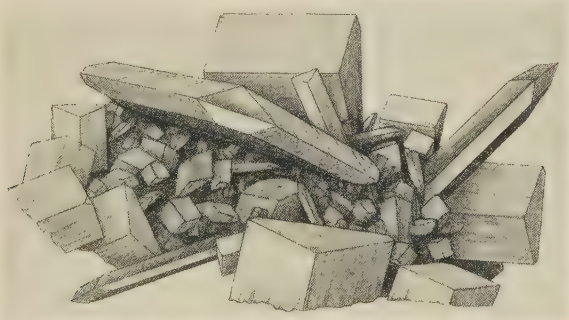


Fig. 640.—Titanite twinned on (100), with Adularia, from Switzerland.

with the exception of the diamond, no facetted mineral possesses a more beautiful fire than sphene.

Fig. 640 represents large pale green twins associated with adularia in a mica-schist from the St. Gothard.

The colour of titanite varies through different shades of brown, yellow, green, and pink; and the lustre is often somewhat resinous; the wide range of colour is doubtless due to the varying proportions of iron and manganese which the mineral contains. The colour is altered on heating.

The large crystals found in crystalline limestones, as in Canada and

New York, are usually deep brown or black in colour; some of these are tabular owing to the predominance of the faces C.

One of the alteration products of ilmenite (known as "leucoxene") appears to be largely a white earthy titanite.

HEMIMORPHITE

Hemimorphite.—Silicate of zinc; $H_2Zn_2SiO_5$; $ZnO = 67{\cdot}6$, $H_2O = 7{\cdot}5$, $SiO_2 = 24{\cdot}9$.

Orthorhombic; symmetry, polar.

$$a : b : c = 0{\cdot}783 : 1 : 0{\cdot}478.$$

B = {010}, C = {001}, m = {110}, t = {301}, s = {101}, e = {011}, e' = {01$\bar{1}$}, v = {12$\bar{1}$}.

mm (110) : (1$\bar{1}$0) = 76° 9′, Cs (001) : (101) = 31° 23′, Ct (001) : (301) = 61° 20′, Bv (010) : (12$\bar{1}$) = 50° 47′, Be (010) : (011) = 64° 28′.

Twins on (001). Cleavage m {110}, perfect; s {101}, C {001}, imperfect. Brittle. Fracture, uneven. H = 5; G = 3·4. Colourless. Streak, white. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}636$, $\beta = 1{\cdot}617$. Birefringence, positive; $\gamma - \alpha = 0{\cdot}022$. Axial plane (100). Acute bisectrix normal to C (001); 2E = 78° 30′. Dispersion, strong; $\rho > v$. Fusible with difficulty (6). Decomposed by hydrochloric acid. Pyro-electric.

With the above description compare crystals from **Altenberg** (Aachen).

Hemimorphite or calamine (Germ. *Galmei, Kieselzinkerz*) was known long ago as a zinc ore, but no distinction was made between the silicate and carbonate; the names calamine and smithsonite have been applied to both, and hemimorphite, a name recalling the most interesting feature of this mineral, was introduced in order to avoid the confusion. The polar character of the mineral is well shown by the glassy crystals from the old zinc mines of Altenberg, which line cavities in a compact ore consisting of the silicate and carbonate; they are generally attached by the antilogous pole, the lower end of Fig. 641; the face B is vertically striated. The pyro-electric property is easily studied by Kundt's method, as described on p. 129; simple crystals become covered, while cooling, with the red lead at the analogous end, and with yellow sulphur at the more acute antilogous end. Supplementary twins like those of Figs. 241 and 242 attract the red lead at both their ends, and show a band of yellow sulphur in the middle where the two antilogous ends meet. The mineral used to be known as "electric calamine." On heating, the crystals remain unchanged up to 340°, and only give up their water at a red heat. The water is therefore to be regarded as "water of constitution," and the mineral must be

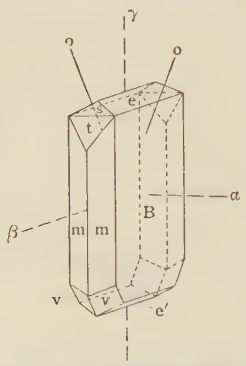


Fig. 641. — Hemimorphite, B {010}, m {110}, e {011}, s {101}, t {301}, e' {01$\bar{1}$}, v {12$\bar{1}$}.

represented as a basic metasilicate $(ZnOH)_2SiO_3$, not as a hydrated orthosilicate $Zn_2SiO_4 . H_2O$.

TALC AND SERPENTINE

Talc.—Silicate of magnesium; $H_2Mg_3(SiO_3)_4$; $MgO = 31{\cdot}9$, $SiO_2 = 63{\cdot}3$, $H_2O = 4{\cdot}8$. Monoclinic (?). Cleavage, pinakoidal {001}, perfect. Sectile. Pliable. $H = 1$; $G = 2{\cdot}7$. Colour, silvery-white. Streak, white. Lustre, pearly. Translucent; $\beta = 1{\cdot}589$, $\alpha = 1{\cdot}539$. Birefringence, negative, strong; $\gamma - \alpha = 0{\cdot}050$. Acute bisectrix normal to the cleavage; $2E = 19°$. Almost infusible. Insoluble in acids. Feel, greasy.

With the above description compare crystallised material from the **St. Gothard.**

Serpentine.—Silicate of magnesium; $H_4Mg_3Si_2O_9$; $MgO = 43{\cdot}7$, $SiO_2 = 43{\cdot}3$, $H_2O = 13{\cdot}0$. Massive. Fracture, splintery. $H = 3$; $G = 2{\cdot}6$. Green, veined with red. Streak, white. Lustre, greasy. Translucent; $\beta = 1{\cdot}57$. Birefringence, weak; $\gamma - \alpha = 0{\cdot}010$. Fusible with difficulty (6). Decomposed by hydrochloric acid.

With the above description compare massive material from the **Lizard** (Cornwall).

These two magnesian silicates may be considered together; they are the common decomposition products of ferro-magnesian silicates, and are usually of secondary origin. Both minerals occur in large masses; talc as talc-schist (*e.g.* at the St. Gothard), when it is associated with chlorite, serpentine, dolomite, magnesite, etc.; serpentine as an alteration product of peridotites and other olivine rocks (*e.g.* at the Lizard, Cornwall).

Talc in the foliated silvery varieties is fairly pure, and shows a hexagonal outline; the crystals, like those of mica and chlorite, are probably monoclinic. The soft, greasy, pliable cleavage-flakes are easily recognised. The interference-figure yielded by a flake of talc resembles at first sight a uniaxial figure, but is in reality biaxial with a very small angle; in this respect and in the strength of the birefringence it might be confused with a cleavage-flake of phlogopite; but talc may be distinguished from any mica by its softness and pliability; the birefringence is stronger than that of a chlorite. The percussion-figure is a three- or six-rayed star, one ray of which is parallel to the axial plane.

Many varieties of talc are coloured, and such usually contain from 1 to 4 per cent of FeO; they may have various shades of yellow, green, or red.

Talc is known not only in foliated masses, but also as the quite compact, structureless variety named "steatite"; this soft, white, or coloured, greasy mineral is also called "soapstone," and, under the name "French chalk," is used by tailors. Much of the white or grey material veining serpentine is steatite. Very remarkable and perfect pseudomorphs of steatite after quartz are found at Göpfersgrün in Bavaria; their origin is difficult to understand, but a similar magnesium silicate can be artificially produced by the action of magnesian solutions upon silica; with these crystals are also found pseudomorphs of the steatite after rhombohedra of dolomite.

Serpentine, even when apparently quite compact, always shows a fibrous structure in thin sections under the microscope, and the fibres show straight extinction with positive extension ; the large masses at the Lizard and similar localities, which are really altered rock masses, present little or no visible structure, contain a considerable proportion of FeO, and are by no means a pure mineral ; the colour varies through different shades of green, red, and yellow. The white streak of all these varieties is characteristic. Where the mineral fills veins, or constitutes seams in massive serpentine, it has a well-marked fibrous structure, the fibres being transverse to the veins, and is a somewhat purer mineral. This fibrous variety with silky lustre is known as " chrysotile." Most of the material known as " asbestos " in the trade is in reality chrysotile, which is worked on an enormous scale in the metamorphic region of Megantic County and Beauce County in the province of Quebec ; it serves most of the purposes for which asbestos is used, although the chrysotile fibres are not so long nor so silky as those of true asbestos. Its infusibility and bad conductivity for heat fit it for incombustible fabrics and paints, firemen's gloves, packing for steam tubes, etc. A variety known as " antigorite " has a platy structure, and shows a more definite interference-figure, with a negative acute bisectrix normal to the cleavage ; the typical specimens come from the Antigorio Valley in Piedmont.

The manner in which, on a microscopic scale, the olivine of rocks becomes serpentinised by transformation into chrysotile along its cracks, and the large pseudomorphs of yellow serpentine after olivine found at Snarum, which were originally supposed to be serpentine crystals, have been mentioned on p. 472.

Some very remarkable pseudomorphs of considerable size have been found at the Tilly Foster Iron Mine, Brewster, New York ; these consist of pale green serpentine with a perfect cubic cleavage. Some have thought them to be pseudomorphs after the oxide of magnesium, periclase, which is known in small cubic crystals ; others regard them as true crystals of serpentine. They are accompanied by serpentine pseudomorphs after calcite, enstatite, hornblende, etc.

Both talc and serpentine are to be regarded as acid (or basic) and not as hydrated silicates, since they only part with their water at a high temperature.

Both serpentine and steatite have been much used for ornamental purposes from early times ; although very soft they are, like other decomposition products, the last results of a series of changes and are therefore not liable to further decay. Some of the very earliest worked articles known consist of steatite ; the coloured varieties (pink and yellow) of this mineral are much used for ornaments by the Chinese at the present day.

The massive serpentine used so largely for decorative purposes, and often known as " serpentine-marble," derives much of its beauty and variety from the veins and patches of white magnesite and talc which it contains, and from splashes of blood-red iron-stained serpentine ; the more soluble constituents of the rocks from which it has been derived furnish veins of dolomite, calcite, and opal. The original pyroxene of the rock

is often represented by the schillerised varieties, bronzite and diallage, described on p. 486. The celebrated "verde antique" is a serpentine-breccia.

Chrysocolla, $CuSiO_3 . 2H_2O(?)$, is the only other silicate of the divalent metals sufficiently common to merit notice. It is a compact amorphous or cryptocrystalline mineral with a lustre like that of opal; the colour is green, blue, or brown; the impure varieties are black, but the streak is whitish. It is a common decomposition product of copper minerals, and a dark impure chrysocolla known as "pitchy copper ore" (Germ. *Kupferpecherz*) is a well-known ore of copper.

We next pass to a small group of minerals which are silicates (or titanates) of divalent with monovalent elements. Of these apophyllite is the only one which is at all common. Clearly, however, some of the minerals considered above, which contain hydrogen, such as dioptase, hemimorphite, chrysocolla, talc, and serpentine, might, in a strict classification, be regarded as belonging to this group.

Apophyllite. — Hydrated silicate of calcium and potassium; $(H,K)_2Ca(SiO_3)_2 . H_2O(?)$; $K_2O = 5{\cdot}3$, $CaO = 25{\cdot}3$, $SiO_2 = 54{\cdot}2$, $H_2O = 15{\cdot}2$ (if H : K = 7 : 1).

Tetragonal (or pseudo-tetragonal ?).

$$a : c = 1 : 1{\cdot}2515.$$

$$C = \{001\},\ A = \{100\},\ p = \{111\}.$$

$$Ap\ (100) : (111) = 52°\ 0',\ Cp\ (001) : (111) = 60°\ 32'.$$

Cleavage C {001}, perfect; *m* {110}, imperfect. Brittle. Fracture, uneven. $H = 4\frac{1}{2}$; $G = 2{\cdot}3$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}53$. Birefringence, positive, very weak; $\epsilon - \omega = 0{\cdot}002$. Easily fusible ($1\frac{1}{2}$). Decomposed by hydrochloric acid.

With the above description compare crystals from **Andreasberg** (Harz).

Apophyllite is often classed among the zeolites, for it exfoliates and gives off water at a comparatively low temperature and is commonly a mineral of secondary origin, found like them in amygdaloidal cavities of basalt. It resembles them also in its power of reabsorbing water after it has been partially dehydrated. The minerals classed below as zeolites (p. 543) are, however, all aluminiferous silicates, and they are peculiar in that on heating they give off their water gradually, to an amount which varies continuously with the temperature and the humidity of the air, whereas apophyllite has been found by Zambonini to give off about half its water between 250° and 270° C., while above this temperature the loss becomes much slower and is complete only on ignition.

The chief interest of apophyllite lies in its optical peculiarity. Brewster found, in 1818, that the cleavage-plates show quite a peculiar interference-figure in white light; the rings do not present the colours of Newton's orders, but in some varieties may consist of violet, greenish-yellow and white circles alternating, without any tint of red. In another variety, as found by Herschel, the rings are only white and black; this

variety he called "leucocyclite." In yet another the colours resemble those shown by brucite (p. 402). Now in Newton's rings (p. 136) the difference of phase, which is the cause of the interference, is due to a difference in the distance traversed by the two interfering rays (Fig. 291), which is nearly the same for all colours, while in the interference-rings shown by a crystal the phase-difference is due to the birefringence, *i.e.* to the difference of velocity of the two rays in the crystal, which may differ considerably for different colours. Hence the true sequence of the colours of Newton's rings is only shown by crystals in which the birefringence does not vary with the wave length; if this is not the case the colours are different. In leucocyclite the birefringence for the different colours is *proportional* to their wave length, so that the dark rings for all colours coincide. Other varieties again show very wide rings (weak birefringence) with brilliant coloration ("chromocyclite"); these were found to be positive for some colours, negative for others, and for some intermediate

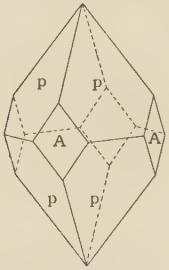


Fig. 642.—Apophyllite, *p* {111}, A {100}.

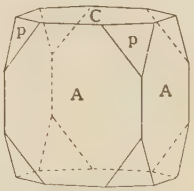


Fig. 643.—Apophyllite, A {100}, C {001}, *p* {111}.

colour isotropic. Differently coloured rings are often shown by different parts of the same crystal.

An explanation is suggested by the fact that the various types of apophyllite rings may be imitated by superposing a plate of a uniaxial positive upon one of a uniaxial negative crystal of varying thickness; and it is therefore possible, as supposed by Klein, that the optical peculiarities of apophyllite may be due to its being an isomorphous mixture of a positive with a negative substance.

In addition to these peculiarities of the uniaxial interference-figure, many apophyllites show in basal section a partition into sectors, some of which are biaxial, negative for blue and positive for red, and with the axial planes crossed, as in brookite.

It is therefore clear that apophyllite is an intergrowth of two or more silicates which differ in their optical properties. Neither of these is known in the pure state, and the chemical composition of the mineral is by no means certain. Most varieties are positive, the birefringence being strongest in those showing "brucite rings"; and since, after heating to 275° C., all varieties show rings of this type, these would seem to belong to a less hydrated silicate. Apophyllite usually contains a small amount of fluorine.

Some Noteworthy Localities:

Andreasberg (Harz).—Colourless or pink glassy crystals of pyramidal habit (forms A,*p*) were found as a vein-mineral accompanying calcite, galena, arsenic and arsenical ores; these crystals are generally without the basal plane (Fig. 642). The faces A {100} are vertically striated.

Poonah (Bombay).—Large white and greenish crystals of tabular habit, with large basal pinakoid (Fig. 643), were found during the construction of the Bombay and Poonah railway in amygdaloidal cavities of the Deccan trap, associated with pale pink stilbite, scolecite, and analcite.

SECTION XVIII

THE SILICATES OF ALUMINIUM

TOPAZ

Topaz.—Fluoriferous silicate of aluminium; $(AlF)_2SiO_4$; $Al_2O_3 = 55{\cdot}4$, $SiO_2 = 32{\cdot}6$, $F = 20{\cdot}7$.[1]

Orthorhombic; symmetry, polar (?).

$$a : b : c = 0{\cdot}528 : 1 : 0{\cdot}477.$$

$C = \{001\}$, $m = \{110\}$, $l = \{120\}$, $o = \{221\}$, $u = \{111\}$, $i = \{223\}$, $d = \{201\}$, $f = \{021\}$, $y = \{041\}$, $n = \{140\}$.

mm $(110) : (1\bar{1}0) = 55°\ 43'$, ll $(120) : (1\bar{2}0) = 93°\ 11'$, Co $(001) : (221) = 63°\ 54'$, Cu $(001) : (111) = 45°\ 35'$, Ci $(001) : (223) = 34°\ 14'$, Cy $(001) : (041) = 62°\ 20'$, Cf $(001) : (021) = 43°\ 39'$, uu $(111) : (1\bar{1}1) = 78°\ 20'$.

Cleavage C {001}, perfect. Brittle. Fracture, sub-conchoidal. $H = 8$; $G = 3{\cdot}5$. Pale yellow. Streak, colourless. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}625$, $\beta = 1{\cdot}618$. Birefringence, positive, weak; $\gamma - \alpha = 0{\cdot}010$. Axial plane (010). Acute bisectrix normal to C (001); $2E = 114°$. Dispersion, strong; $\rho > v$. Infusible. Decomposed with difficulty by sulphuric acid.

With the above description compare crystals from **Schneckenstein** (Saxony).

Topaz is of interest as one of the fluoriferous silicates found commonly in those veins of granite or gneiss which are supposed to have been filled by the action of fluoriferous vapours, and often contain cassiterite (see p. 413); in these veins topaz is accompanied by tourmaline, apatite, mica, and fluor. Topaz is one of those finely crystallised minerals which must have attracted attention in early times; its name is the *topazius* of Pliny, but this evidently refers to a different mineral, probably to chrysolite, since he derives the word from the name of an island in the Red Sea. On the other hand, the Roman *chrysolithus* was probably our topaz.

The hardness, transparency, fairly high refractive index, and variety of colour, render topaz valuable as a gem stone.

The crystals can usually be recognised and orientated by the perfect basal cleavage and the vertical striation of the prism-faces. In the Schneckenstein crystals (Fig. 644) the basal plane is sometimes larger than as shown in the figure, and the other forms are only small faces on its edges.

[1] In analyses of fluoriferous silicates the bases are customarily represented as oxides; but since in fact some oxygen is replaced by the fluorine, the sum of the percentages will exceed 100 by an amount equal to the oxygen-equivalent of the fluorine.

Doubly terminated crystals are rare ; this we have already seen to be the case with the pyro-electric mineral hemimorphite, and most topaz crystals seem to be pyro-electric in the direction of the vertical axis ; the symmetry is therefore probably polar. Some doubly terminated crystals become similarly electrified at the two ends, and may be supplementary twins, like those of hemimorphite (Fig. 242). On the other hand, both natural and artificial etched figures appear to accord with holosymmetry.

The interference-figure, with its positive bisectrix normal to the plate, is beautifully seen through a cleavage-flake, but the axial angle is so large that the optic axes are rarely visible within the field of view of the microscope except with oil immersion. The optic axial angle varies considerably in different specimens. Penfield has shown that the mineral always contains a little water, and that the axial angle 2E diminishes, from 127° to 84°, as the proportion of water increases from 0·2 to 2·5 per cent ; at the same time the proportion of fluorine decreases from 20 to 16 per cent.

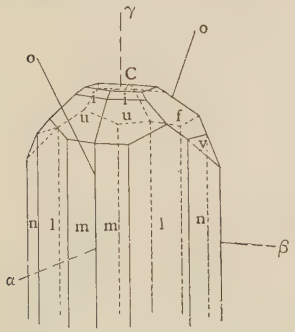


Fig. 644.—Topaz, *m* {110}, *l* {120}, *n* {140}, *u* {111}, *i* {223}, *y* {041}, *f* {021}, C {001}.

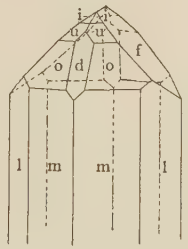


Fig. 645.—Topaz, *m* {110}, *l* {120}, *o* {221}, *d* {201}, *u* {111}, *i* {223}, *f* {021}.

The water found in the analyses is therefore due to the partial replacement of F by OH in the formula given above. The value 2E = 114° given above corresponds to 0·93 per cent of water (crystals from Saxony). It is not known for certain to what the colour is due ; the Schneckenstein crystals are mostly pale yellow, but some are colourless, as are also crystals from Japan, Mexico, and Utah (Fig. 645) ; the Brazilian crystals are brown ; large crystals from the Urulga River in Siberia (Fig. 646) are deep wine-yellow ; many of those from Mursinka in the Urals and from Adun-Chilon are pale blue. Most of the brown crystals turn to rose-red on heating, and Brazilian topazes are sometimes treated in this way before being cut as gems ; some of the yellow varieties lose their colour altogether when heated.

Topaz often contains microscopic cavities filled with liquids of more than one kind, which were investigated by Brewster. One of these, which has received the name " brewsterlinite," has been found to have the very low refractive index 1·13 and appears to be, at least in part, liquid carbon dioxide.

Some Noteworthy Localities:

Schneckenstein (near Auerbach, in Saxony).—Cavities in the so-called *Topasfels*, which is a brecciated mass of tourmaline-quartz rock cemented by topaz and quartz, are lined with crystals of topaz (Fig. 644), sometimes associated with cassiterite, apatite, and chalcopyrite. With these is usually a white or yellowish earthy kaolin.

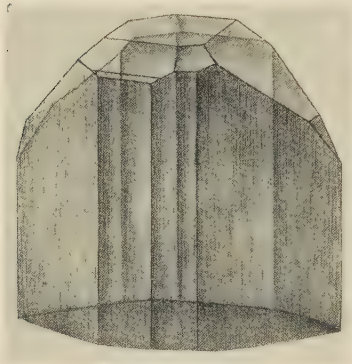


Fig. 646.—Topaz from the Urulga River.

Russia. — Several localities in the Nerchinsk district, Siberia, have afforded fine topaz crystals in the druses of granite; among the best are perhaps the pale blue crystals (usually without C and terminated by large faces of *f* {021}, which are often coated with an opaque whitish crust) found with smoky quartz, beryl, and orthoclase in the Adun-Chilon Range, and crystals of various colours from the Urulga River.

Fig. 646 represents one of the six enormous pale brown crystals from the Urulga River which are preserved under cover in the British Museum, since it is believed that these lose their colour when exposed to daylight.

Large blue crystals, usually characterised by the large basal plane, from the granite of Mursinka in the Urals, are associated with smoky quartz, lepidolite, orthoclase, and masses of tabular albite crystals (Fig. 647).

Fig. 647.—Topaz, with Quartz and Orthoclase, from Mursinka (Urals).

Brazil. — The Brazilian crystals in mineral collections are generally separated from the matrix, since in Minas Geraes, where they are found in large quantities, they occur in a soft talc schist, or in pockets of kaolin, with quartz, rutile, etc. Sometimes the topaz is enclosed or partially enclosed in quartz. The crystals are deep brown, usually simple combinations of {110}, {120}, and {111}, without the basal plane.

Japan.—Colourless crystals of the habit shown in Fig. 645 are found in stanniferous sands, with other minerals derived from the decomposed granite of the Kiso Range, in Mino province.

Crystals of a similar acute habit are found in the stanniferous sands of **Durango** in Mexico, where they have been derived from a trachyte. Somewhat similar crystals are found in rhyolite at **San Luis Potosi,** and this

occurrence closely resembles that of the **Thomas Mountains** in Utah, where limpid crystals like Fig. 644 are found in druses of the rhyolite with crystals of quartz and sanidine.

ANDALUSITE AND CYANITE

Andalusite.—Silicate of aluminium; Al_2SiO_5; $Al_2O_3 = 62{\cdot}9$, $SiO_2 = 37{\cdot}1$. Orthorhombic.

$$a : b : c = 0{\cdot}986 : 1 : 0{\cdot}702.$$

$$C = \{001\},\ m = \{110\}.$$

$$mm\ (110) : (1\bar{1}0) = 89°\ 12'.$$

Cleavage {110}. Brittle. Fracture, uneven. H = 7½; G = 3·1. Reddish brown. Streak, colourless. Lustre, vitreous. Translucent; $\beta = 1{\cdot}638$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}011$. Axial plane (010). Acute bisectrix normal to C; $2H = 96°\ 30'$. Pleochroic; β and γ olive-green, α dark blood-red. Infusible. Insoluble in acids.

With the above description compare crystals from **Morbihan** (Brittany).

Cyanite.—Silicate of aluminium; Al_2SiO_5; $Al_2O_3 = 62{\cdot}9$, $SiO_2 = 37{\cdot}1$. Anorthic.

$$a : b : c = 0{\cdot}899 : 1 : 0{\cdot}697.$$

$$\alpha = 90°\ 23',\ \beta = 100°\ 18',\ \gamma = 106°\ 1'.$$

$$C = \{001\},\ A = \{100\},\ B = \{010\},\ m = \{110\},\ M = \{1\bar{1}0\},\ q = \{011\}.$$

$$CB\ (001) : (010) = 86°\ 36',\ CA\ (001) : (100) = 79°\ 10',\ AB\ (100) : (010) = 73°\ 39',$$
$$Am\ (100) : (110) = 34°\ 13',\ AM\ (100) : (1\bar{1}0) = 48°\ 30',\ Cq(001) : (011) = 34°\ 18'.$$

Cleavage {100}, perfect; {010}, imperfect. Brittle. Fracture, somewhat fibrous. H (on A) = 7 parallel to edge AC, 4½ parallel to edge AB; (on B) = 7. G = 3·6. Blue to white. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}72$. Birefringence, negative, rather strong; $\gamma - \alpha = 0{\cdot}016$. Acute bisectrix and axial plane nearly normal to A. Axial plane inclined at 30° to the edge AB. $2V = 82°\ 30'$. Infusible. Insoluble in acids.

With the above description compare crystals from the **St. Gothard.**

Andalusite and cyanite possess the same percentage composition; and this belongs also to a third mineral distinct from both, namely **sillimanite** or fibrolite.

Andalusite is found in schists which are the result of the metamorphic action of granite and similar rocks. The best known specimens are the large crystals found in the argillaceous schist at Rohan in Morbihan (Brittany). These are large uneven prisms, generally much altered, and partly converted into kaolin. Very similar are the specimens from the Lisens Alp in the Tyrol (Fig. 648). The unaltered mineral is found in Minas Geraes (Brazil), as water-worn crystals, which show the remarkable dichroism by appearing green or red according to the direction in which they are viewed; gem stones cut from this mineral display a beautiful effect for the same reason, if suitably shaped.

The Morbihan crystals belong to the variety known as "chiastolite," from the Greek letter χ ($\chi\iota\acute{\alpha}\zeta\omega$), on account of its black carbonaceous enclosures, which appear as a cruciform pattern when the crystals are

cut across (Fig. 649). The disposition of this black material within the crystal is very curious; the various patches are wedge-shaped, becoming thinner towards one end of the crystal and thicker towards the other; the central core is sometimes hour-glass shaped, becoming thicker from the centre towards both ends; this peculiar structure of chiastolite has been supposed to indicate a skeletal growth of the crystals, in which the carbonaceous residue has followed the lines of growth during the conversion of the slate into crystals of andalusite. These crystals were known as "macles" in very early times, and the origin of the name is supposed to be the Latin term *macula*, used for the heraldic lozenge; it is believed that this device may have been introduced into their armorial bearings by the family of the Vicomte de Rohan to represent the chiastolite of their neighbourhood.

Cyanite, or disthene, is a mineral of very different appearance; its

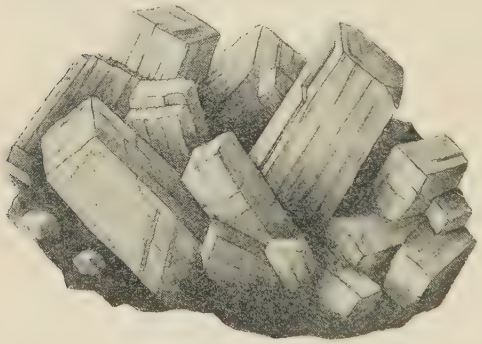


Fig. 648.—Andalusite on Mica Schist, from Lisens Alp (Tyrol).

Fig. 649.—Chiastolite from Massachusetts.

properties are best studied in the pale blue blade-shaped crystals which accompany staurolite in a white paragonite- (mica-) schist at Monte Campione in Canton Tessin in Switzerland. The cyanite and staurolite are sometimes united in regular position, as described on p. 96 (Fig. 226). The extraordinary difference of the hardness in different directions (p. 123) can easily be tested by scratching a crystal with a knife. The name disthene, which was given to the mineral by Haüy, may be taken as recalling this property (δίς and σθένος, *i.e.* "having two strengths"), though it was originally given in allusion to the observation that some crystals develop positive and others negative electricity when rubbed. The other name, cyanite, refers to the blue colour.

Both andalusite and cyanite when raised to a high temperature (about 1350° C.) become converted into an aggregate of fibres which give straight extinction, have a uniform hardness of $6\frac{1}{2}$, and a specific gravity of 3·2, the chemical composition remaining unchanged. These properties show the resulting product to consist of **sillimanite**, a fibrous orthorhombic mineral found in gneiss and schists, especially those which contain cordierite.

The compact sillimanite known as fibrolite has often been used in the manufacture of prehistoric implements and ornaments; it is sometimes wrongly called jade.

The differences in constitution between the above three minerals have not yet been established. Groth has suggested that the more stable compound, cyanite, is a metasilicate $(AlO)_2SiO_3$, and the less stable andalusite an orthosilicate $Al(AlO)SiO_4$; just as enstatite is more stable than olivine among the magnesian silicates.

THE CLAYS

Corresponding to the scaly talc and the amorphous steatite among the magnesian silicates are the family of scaly and amorphous minerals known as clays among the aluminous silicates. The most important of these is **kaolinite** or china-clay, which occurs as a decomposition-product of felspar. For commercial purposes, for the manufacture of porcelain and china, it is worked on a large scale in certain decomposed granites; for example at St. Austell in Cornwall, where it occurs in vast masses associated with a tourmaline-quartz rock; the name is of Chinese origin, like the industry for which the mineral is worked. A silvery-white powdery kaolinite found at Amlwch in Anglesey is seen under the microscope to consist entirely of minute hexagonal plates and tapering pyramids, with perfect basal cleavage, which belong to the monoclinic system and resemble in form some crystals of muscovite (p. 530). The axial plane is perpendicular to the plane of symmetry; but, unlike muscovite, kaolinite has its (negative) bisectrix inclined to the cleavage-face at an angle of 15°-20° to the normal. The axial angle is very wide. The refractive indices and the birefringence are lower than in muscovite. This and other pure white specimens of kaolinite have the composition $H_4Al_2Si_2O_9$, corresponding exactly to serpentine, $H_4Mg_3Si_2O_9$; but much kaolinite is coloured yellow or brown and is impure, containing ferric oxide or hydrate. Common clay is generally a mixture of kaolinite with many other decomposition-products, mainly hydrated silicates or hydrates of alumina and iron. Many such substances have been distinguished by special names, but some of them are probably mixtures of colloidal substances, of indefinite composition and containing variable amounts of water and of "adsorbed" salts. It also contains a considerable proportion of finely ground felspar, quartz, and mica. The plasticity of clay and its impermeability to water, qualities which make it so important, may be partly due to its minutely scaly texture, which may also be the cause of its unctuous feel, but they may also be due in part to the presence of the colloidal constituents. Most clays can be recognised by the peculiar earthy odour which they yield when breathed upon.

"Lithomarge" (Germ. *Steinmark*) is a compact kaolinite which sometimes resembles steatite in appearance, but has not the same greasy feel.

Kaolinite is a decomposition-product of many aluminous silicates, and is consequently found as a pseudomorph after several minerals, *e.g.* orthoclase, albite, leucite, beryl; but it is not found as a result of the alteration

of anorthite. Pseudomorphs after large porphyritic Carlsbad twins of orthoclase are plentiful in the decomposed granite of St. Austell. The name *kaolin* is frequently used in a general sense for such clayey decomposition-products, though some of them may not consist of pure kaolinite.

The variously coloured material used by the Chinese for ornaments and images, and consequently named " agalmatolite," is really of two sorts ; some is steatite, and some is a compact aluminous silicate having the composition $H_2Al_2(SiO_3)_4$; the latter corresponds to a member of the clay family named **pyrophyllite,** which is sometimes found in radially grouped foliated masses consisting of cleavable biaxial crystals.

SECTION XIX

THE ALKALINE SILICATES

LEUCITE

Leucite. — Silicate of potassium and aluminium; $KAl(SiO_3)_2$; $K_2O = 21{\cdot}6$, $Al_2O_3 = 23{\cdot}4$, $SiO_2 = 55{\cdot}0$. Pseudo-cubic. Common form, icositetrahedron {211}. Cleavage, dodecahedral, very imperfect. Brittle. Fracture, conchoidal. $H = 5\frac{1}{2}$; $G = 2{\cdot}5$. Colourless. Streak, white. Lustre, vitreous. Transparent; very weakly birefringent and biaxial. $\beta = 1{\cdot}508$. Infusible. Decomposed by hydrochloric acid.

With the above description compare crystals from **Vesuvius.**

Leucite is noteworthy as one of the minerals which have contributed most to our knowledge of pseudo-symmetry. Although crystallising in the most perfect icositetrahedra {211} (the "leucitohedron"), it was found by Brewster to be birefringent and even biaxial in parts; the peculiarity was at first attributed to a lamellar structure. As described on p. 206, it was first shown by vom Rath that the angles were not those of the cubic icositetrahedron, and that the mineral was traversed by twin-lamellæ parallel to (101) and (011), so that it must be described as tetragonal. It is in accordance with this view that the upper face (112) is more readily attacked by solvents than the lower faces (211) and (121). Since, however, it has been found that there are also twin-lamellæ parallel to (110) and (1$\bar{1}$0), and that the crystals consist of overlapping biaxial material, the mineral must be regarded as either orthorhombic or monoclinic; the appearance presented by thin sections parallel to (001) and (111) is shown in Figs. 390, 391 (p. 206). In some crystals a positive bisectrix with a small axial angle emerges *normal* to each cube-face, and this indicates orthorhombic rather than monoclinic symmetry.

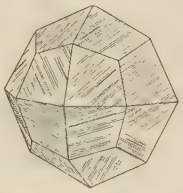


Fig. 650. — Leucite, showing twin striations.

It was shown by Klein that when a leucite section is heated while under observation between crossed nicols, at a certain temperature, which is near 700° C., a dark shadow seems to extend across the section, which then becomes isotropic; on cooling, twin-lamellæ reappear, though not always in the same positions as before. Rosenbusch showed that at the

above temperature the inequalities of the crystal faces due to the edges of the twin-lamellæ also disappear, and the faces become smooth and bright (p. 207). There can be little doubt, therefore, that at high temperatures the mineral really belongs to the cubic system, and that it crystallised from the rock-magma at a high temperature as a cubic mineral and broke up into orthorhombic lamellæ on cooling, so that the ordinary crystals of leucite are paramorphs.

Leucite generally contains abundant inclusions of other minerals which are situated in regular lines following the contour of the crystal and not influenced by the optical boundaries -another argument in favour of the above view.

The double refraction is so slight (not more than 0·001) that in thin sections leucite may appear isotropic, but the twin-lamellation is generally discernible (especially with a sensitive gypsum plate, p. 197), and betrays the birefringence of the mineral.

By treatment with a solution of sodium chloride or carbonate, Lemberg has succeeded in converting leucite into analcite, the corresponding sodium compound, whose formula, however, differs from that of leucite in containing one molecule of water ; and by treatment with fused sodium chloride it is converted into an (anhydrous) sodium-leucite. Leucite is, in fact, an unstable compound, and as found in Nature is usually white and opaque owing to conversion into analcite, or ultimately into kaolin. The name is derived from λευκός, white.

Some Noteworthy Localities :

Vesuvius.—Porphyritic crystals altered in this manner are found in the old lavas of Vesuvius, where they are accompanied by porphyritic augite and orthoclase in a grey porous ground-mass ; small clear transparent crystals are sometimes found in the modern lava, or fall like a shower of hailstones in an eruption ; clear crystals are also found with meionite and sanidine in the ejected dolomite blocks.

Some of the lavas of **Capo di Bove** near Rome, of the **Eifel**, and of the **Kaiserstuhl** in Baden, consist almost entirely of leucite and augite.

NEPHELINE

Another alkaline silicate often associated with leucite in the group of alkaline rocks (phonolite, tephrite, leucite-basalt, etc.), is **nepheline**, which has a composition nearly represented by the formula $K_2Na_6Al_8Si_9O_{34}$. Glassy, colourless, or white hexagonal prisms of nepheline are found in druses of the ejected blocks of Monte Somma, usually accompanied by sanidine, or by garnet, mica, and hornblende. They belong to the hexagonal system, have a fair prismatic and basal cleavage, and possess weak, negative double refraction : H = $5\frac{1}{2}$, G = 2·6. Etching with hydrofluoric acid produces similar, unsymmetrical figures upon the six prism-faces, showing that the mineral possesses only a polar axis of hexagonal symmetry, and belongs to Class XIV of pp. 91-92 ; it is the only representative of this class among minerals ; the crystals are usually, however, supple-

mentary twins and simulate holosymmetry. Nepheline possesses nearly the same specific gravity, refractive power, and birefringence as quartz, and in thin sections is only to be distinguished from quartz by the sign of the birefringence. From apatite, which it resembles in this respect, it is distinguished by its lower refractive index, which is almost the same as that of Canada balsam.

Nepheline, like leucite, is far from stable, and many of the porphyritic crystals found in soda-bearing rocks, especially older plutonic rocks, are called elæolite (from ἔλαιον, oil) on account of their greasy lustre, which is probably due to incipient alteration ; they generally contain more water than glassy nepheline.

The elæolite-syenite of southern Norway contains large, opaque, grey hexagonal prisms of the mineral associated with orthoclase, oligoclase, augite, ægirite, etc. Even among the Vesuvian specimens are to be found white hexagonal prisms of opaline lustre, which have been regarded as distinct minerals, and have been named " davyne " and " cavolinite " ; these seem to be really altered nepheline.

The varieties, nepheline (proper) and elæolite, may be compared, as regards their freshness and mode of occurrence, with sanidine and orthoclase (p. 516).

The formula given above for nepheline approximates to $R'AlSiO_4$. An artificial soda-nepheline, $NaAlSiO_4$, and an artificial potash-nepheline, $KAlSiO_4$, have both been made, and seem to correspond to the mineral, so that the formula $(K,Na)AlSiO_4$ may represent its true composition.

THE SODALITE GROUP

Another characteristic alkali-silicate of the elæolite-syenites is one which contains also chlorine, namely, the cubic substance **sodalite,** $Na_4(AlCl)Al_2(SiO_4)_3$, often found as a blue constituent of the rock, and the same mineral is found in druses of the ejected sanidine blocks of Mount Vesuvius in beautiful white dodecahedra accompanying meionite, augite, and leucite, or garnet and hornblende. The blue mineral named **haüyne,** found in rounded dodecahedra in druses of the ejected calcareous blocks of Vesuvius, seems to be isomorphous with sodalite ; this mineral is remarkable as one of the few silicates which contain sulphur, and its formula, if expressed as $Na_2Ca(AlSO_4Na)Al_2(SiO_4)_3$, is analogous to that of sodalite.

Now **lapis-lazuli**, the beautiful blue substance found in Persia, and prized as an ornamental stone for ages, is also a soda-lime-alumina silicate containing sulphur and chlorine ; it is natural to suppose that it bears a close relationship to the sodalite-haüyne group. For many years the ultramarine made from lapis has been replaced by an artificial colouring matter which is manufactured upon a large scale, and is prepared by the fusion of kaolin with sodium carbonate and sulphur. The chemical composition of the artificial ultramarine is not certain, but it is highly probable that its rich blue colour is due to the presence of the compound $Na_4(AlS_3Na)Al_2(SiO_4)_3$, which may conveniently be called **lazurite.**

Lapis-lazuli was formerly supposed to be a simple mineral, but Brögger

and Bäckström have shown that it is really a rock consisting of diopside, amphibole, muscovite, calcite, and iron pyrites, together with a blue cubic mineral; this blue mineral has practically the composition just ascribed to lazurite, but is probably contaminated by isomorphous intermixture with haüyne and sodalite, which introduce a certain proportion of calcium and of chlorine. Lazurite is therefore to be regarded as a cubic mineral belonging to the sodalite-haüyne group, and in this group the divalent radicals $(AlCl)''$, $(AlSO_4Na)''$, $(AlS_3Na)''$ are supposed to be capable of mutual replacement.

True lapis-lazuli is a deep blue opaque substance variegated by bright specks of iron pyrites; the ancient quarries, which were visited by Marco Polo in 1271, are in Badakshan, above the valley of the river Kokcha, which flows into the Oxus; the precious mineral is found in a dark-coloured and a white limestone, and is extracted by heating the limestone with fires, and then breaking out the lapis-lazuli with hammers. It is probable that all the lapis of antiquity, for which various localities were given, really came from this spot. The mineral is called *sapphiros* by Pliny.

SECTION XX

THE FELSPAR GROUP

The minerals of the felspar family derive their chief scientific interest from the fact that they are the most important of all rock constituents; indeed, the classification of most rocks depends to a large extent upon the particular felspar which they contain; the identification of felspars under the microscope is a matter of extreme moment to the geologist, and for this reason their optical properties have been the subject of much study. The rock-forming felspars occur for the most part only as small or microscopic crystals; but the potash-felspar, orthoclase, occurs in large crystals, and in considerable masses, which are quarried for use in the manufacture of porcelain. This mineral, by its decomposition, also furnishes the china-clay of commerce.

Feldspath is an old German or Swedish name of doubtful signification, which was in use as early as 1750. Several different varieties of the mineral were distinguished, first by their crystallographic, then by their chemical characters. The name orthoclase (ὀρθός, upright; κλάσις, fracture) was used by Breithaupt (1823) to denote felspar with a rectangular cleavage (*i.e.* monoclinic felspar), and the name plagioclase (πλάγιος, slanting) was subsequently applied to the anorthic felspars whose cleavage-angle is not 90°. He also introduced the name oligoclase for the soda-felspar from Stockholm, which had been distinguished as a new mineral by Berzelius, and possessed an ill-defined cleavage. These names are universally employed at the present time. While, however, the potash-felspar, orthoclase, became more firmly established as a definite species belonging to the monoclinic system, further study of the felspar containing soda and lime indicated that the composition of plagioclase is extremely variable, and led to the use of a great number of names to distinguish the varieties. Those most rich in lime were called anorthite, a name used by G. Rose (in 1823) for the glassy crystals found in the volcanic ejections of Vesuvius; those most rich in soda were called albite, a name originally used by Berzelius for a felspar from Fahlun in Sweden; many intermediate varieties were referred either to oligoclase, or to labradorite, a chatoyant mineral from Labrador. The various species were distinguished by their cleavage-angles and blowpipe reactions, and by their specific gravity. An important character by which plagioclase could generally be distinguished from orthoclase was the multiple twinning of the former. The plagio-

clase felspars usually consist of fine twin-lamellæ parallel to B, whereas in orthoclase B is already a plane of symmetry, and therefore cannot be a twin-plane. Consequently in plagioclase (Fig. 254) the C-cleavage is traversed by fine bands due to the oscillatory combination of C, C_1 of Fig. 252; these planes are inclined to one another at 7° 12′ in albite, and at 8° 20′ in anorthite; they yield two reflecting surfaces, easily seen when C is viewed by reflected light. This is known as the "twin-striation of plagioclase," and is clearly visible on cleavage-fragments.

All felspars were naturally referred to one and the same family on account of the remarkable similarity of their cleavage, crystalline form, hardness, lustre, and specific gravity; but as their chemical nature became better understood they appeared to be widely different in composition. The potash-felspar, orthoclase, and the soda-felspar, albite, have a similar constitution, $R'AlSi_3O_8$, and yet belong to different systems, while the lime-felspar, anorthite, has a totally different constitution, $R''Al_2Si_2O_8$, and yet appears to be completely isomorphous with albite. The different varieties of plagioclase contain all these elements, and are scarcely to be divided into distinct species.

In 1864 Tschermak propounded the theory of the felspar group which has now found universal acceptance. According to this theory the plagioclases are isomorphous mixtures of albite and anorthite, and can be represented as $m NaAlSi_3O_8 + n CaAl_2Si_2O_8$. The only pure soda-felspar is albite ($SiO_2 = 68{\cdot}8$ per cent); the only pure lime-felspar is anorthite ($SiO_2 = 43{\cdot}2$ per cent).

In the soda-lime-felspars it was found that as the soda increases the silica increases and the alumina diminishes; but as the lime increases the silica diminishes and the alumina increases. These relations are in complete accordance with the above formula.

The names previously used rather indefinitely for the intermediate varieties can now receive greater precision of meaning as follows—using Ab to denote albite, and An for anorthite:

Oligoclase, Ab_6An to Ab_3An ($SiO_2 = 64{\cdot}7$ to $61{\cdot}7$).
Andesine, Ab_3An to $AbAn$ ($SiO_2 = 61{\cdot}7$ to $55{\cdot}0$).
Labradorite, $AbAn$ to $AbAn_3$ ($SiO_2 = 55{\cdot}0$ to $48{\cdot}5$).
Bytownite, $AbAn_3$ to $AbAn_6$ ($SiO_2 = 48{\cdot}5$ to $45{\cdot}8$).

Since most of the plagioclases also contain potash, we have to suppose either that monoclinic orthoclase can form isomorphous mixtures with anorthic plagioclase, or that potash-felspar is dimorphous, and that a modification exists belonging to the anorthic system and capable of entering into these mixtures.

The latter view is supported by a discovery made in 1876 by Descloizeaux, who showed that many potash-felspars are optically anorthic; he united these under the name microcline, which had been applied by Breithaupt to a chatoyant felspar from Fredriksvärn in Norway on account of its cleavage-angle (89° 38′) differing but slightly from a right angle (*μικρός*, *κλίνω*). A beautiful green mineral, known as

"amazon-stone," from the Ilmen Mountains and other localities, was the most conspicuous example of these anorthic potash-felspars. For later views on the relations of orthoclase and microcline see, however, p. 519.

ORTHOCLASE

Orthoclase.—$KAlSi_3O_8$; $K_2O = 16{\cdot}9$, $Al_2O_3 = 18{\cdot}3$, $SiO_2 = 64{\cdot}8$. Monoclinic.

$$a : b : c = 0{\cdot}658 : 1 : 0{\cdot}555. \quad \beta = 63° 57'.$$

$m = \{110\}$, $C = \{001\}$, $B = \{010\}$, $x = \{10\bar{1}\}$, $y = \{20\bar{1}\}$, $n = \{021\}$, $o = \{\bar{1}11\}$.

mB (110) : (010) = 59° 24′, mm (110) : ($1\bar{1}0$) = 61° 13′, Cx (001) : ($\bar{1}01$) = 50° 17′, Cy (001) : ($\bar{2}01$) = 80° 18′, Cn (001) : (021) = 44° 56½′.

Twinned on (021) (Baveno law). Cleavage C, B, perfect; m, imperfect. Brittle. Fracture, conchoidal. H = 6; G = 2·56. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}523$, $\alpha = 1{\cdot}519$. Birefringence, negative, weak; $\gamma - \alpha = 0{\cdot}007$. Axial plane perpendicular to (010). Acute bisectrix inclined at 85° to the normal of (001) and 21° to the normal of (100). Extinction ($a\alpha$) on B = +5°. 2E = 120°. Fusible (5). Insoluble in acids.

With the above description compare crystals (adularia) from the **St. Gothard.**

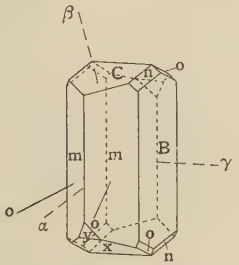


Fig. 651.—Orthoclase, B {010}, C {001}, m {110}, x {10$\bar{1}$}, y {20$\bar{1}$}, o {$\bar{1}$11}, n {021}.

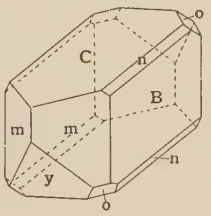


Fig. 652. — Orthoclase, B {010}, C {001}, m {110}, y {20$\bar{1}$}, o {$\bar{1}$11}, n {021}.

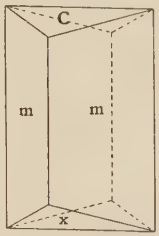


Fig. 653. — Orthoclase (Adularia), m {110}, C {001}, x {10$\bar{1}$}.

The usual crystals of **orthoclase,** which occur in druses in many granites, show the forms of Fig. 651. Typical examples are the white crystals of the Mourne Mountains, of the Colorado granite, and of the Cornish clay works. Three distinct habits may be recognised: (1) "Baveno habit" of Fig. 652, when the crystals are elongated along the edge BC, *e.g.* the pink felspar of the Baveno granite quarries; (2) "Sanidine habit," like Fig. 664, when the crystals are tabular along B, *e.g.* the large, dull grey felspar of the trachyte of the Drachenfels, to which this name was first applied (from σανίς, a tablet)—more perfect examples are the small, limpid, glassy crystals found in druses of the felspar blocks ejected from Mount Vesuvius; (3) "Adularia habit," Fig. 653, characteristic of the glassy crystals from the St. Gothard district, and called after the old name of that range or one of its spurs (Adula).

The cleavage-faces C, B can always be recognised on orthoclase, and the more perfect (C) is easily distinguished; owing to cleavage-cracks

the face C has a somewhat pearly lustre; the prismatic cleavage m is very imperfect, but is important, for it affords ready means of orientating a crystal of orthoclase. If the prism-cleavages be placed vertical and the upper C-cleavage sloping downwards towards the observer, the crystal is placed in the normal position in which the above diagrams are drawn. The face x is easily recognised as a plane almost symmetrical to C at the back of the crystal; this gives an apparently orthorhombic form to the crystals of adularia, Fig. 653; y, on the contrary, is nearly at right angles to C; the prism m is often accompanied by smaller faces of z {130}.

The clino-pinakoid B is often vertically striated. The ortho-pinakoid A {100} is very rarely present.

In descriptions of felspar it has usually been customary (following Haüy) to denote—

C {001} by P
B {010} by M
m {110} by T or l.

The twinning of orthoclase takes place on three laws which are named after typical localities in which specimens illustrating them were found.

(1) Carlsbad law: two individuals are united by the face B (Fig. 656) or partially interpenetrate (Figs. 654, 655), and are twinned by hemitropy

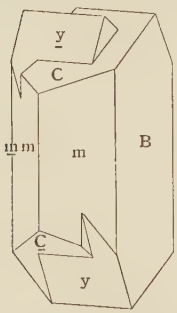


Fig. 654. — Orthoclase twinned on axis [001] (Carlsbad Law).

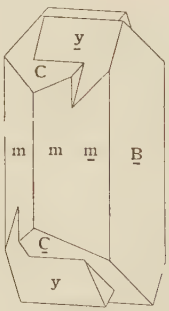


Fig. 655. — Orthoclase twinned on axis [001] (Carlsbad Law).

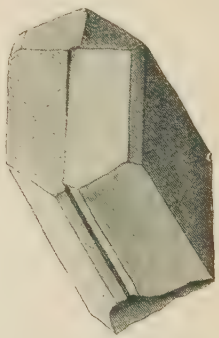


Fig. 656. — Orthoclase, top of a Carlsbad Twin (Forms: B, C, x, m, o).

about the vertical axis or prism-edge [001]. Since C and x are nearly symmetrical, C of one crystal nearly falls into a plane with $\underline{x}$ of the other (Fig. 656); they should really make an angle of 1° 50′ with each other, but even if the angle cannot be detected by the eye, it is easy to see that, of the two faces which appear to fall into a plane, one is parallel to a cleavage while the other is not. Fig. 656 shows not only that C, $\underline{x}$ are not quite in a plane, but also that C is frequently dull while $\underline{x}$ is smooth and bright. The crystals may be grouped as in either Fig. 654 or Fig. 655, and these are sometimes distinguished as right-handed and left-handed Carlsbad twins.

(2) Baveno law: two individuals (generally of the Baveno habit) are twinned about n (021), and are united along that plane. Since the angles

C*n* and B*n* are very nearly 45°, the twinned crystal is an almost rectangular prism and may at first sight be mistaken for a single individual, but examination of the cleavage will show that two C-faces are adjacent at one edge, and two B-faces at the opposite edge. The two ends of the crystal show a characteristic diagonal line of union ; at one end faces $m\underline{m}$ and $y\underline{y}$ meet at small salient angles across this line, as shown in Fig. 657 ;

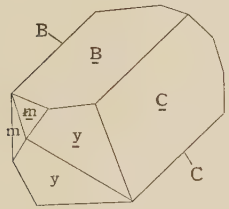


Fig. 657.—Orthoclase twinned on (021) (Baveno Law).

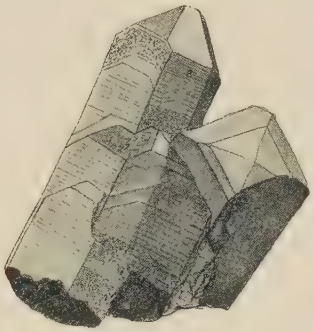


Fig. 658.—Orthoclase, Baveno Twin, with Quartz.

at the other end are corresponding re-entrant angles. Here $m\underline{m} = 10° 34'$, $y\underline{y} = 13° 42'$. Fig. 658 represents a characteristic Baveno twin attached to a crystal of quartz.

Repetition on this law, with inclined twin-planes, may give rise to a quartet as in Fig. 659, in which the rectangular prism is now bounded by *four* faces, C, corresponding to the more perfect cleavage ; the re-entrant

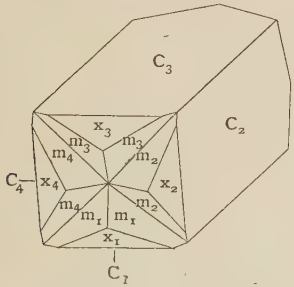


Fig. 659.—Orthoclase, Quartet, twinned on {021}.

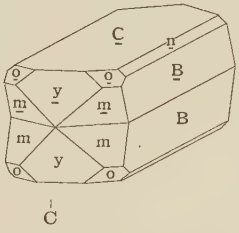


Fig. 660.—Orthoclase twinned on (001) (Manebach Law).

angles give a stellate appearance to the end of the crystal ; a fifth crystal twinned upon No. 4 would almost coincide with No. 1. It is clear from Fig. 657 that a quartet may equally well be bounded by four B-faces.

Complex groups twinned on the Baveno law are common in adularia.

(3) Manebach law : two individuals twinned upon C (001) are united along that plane, Fig. 660. Here the faces B, $\underline{B}$ of the two individuals fall into a single plane.

The Baveno and Manebach laws are sometimes combined in a single

twin-group ; it is then often difficult to say which law is operating. Thus in Fig. 659 the individuals 1 and 3 are in almost exactly the same relative positions as the two individuals of Fig. 660 ; in Fig. 660 the faces C, C are parallel ; in Fig. 659 the faces C_1, C_3 are inclined at 14′ (since $Cn = 45° 3\frac{1}{2}'$ and, therefore, $C_1C_2 = 90° 7' = C_2C_3$). It would therefore require very accurate measurements to say whether Fig. 659 is a Baveno quartet, or an interpenetration of two Manebach twins (C_1C_3 and C_2C_4) twinned together on the Baveno law.

These complex twin-groups illustrate well the pseudo-tetragonal character of orthoclase about the axis of the zone [C B].

Three varieties of orthoclase may be distinguished : (1) orthoclase proper : crystals (frequently Carlsbad twins) of the habit of Fig. 651 or 652, or sometimes of "sanidine habit," and commonly whitish, yellowish or pinkish and semi-opaque from incipient alteration, occurring as constituents of granites and similar plutonic rocks ; (2) "sanidine" : glassy, transparent crystals, usually of "sanidine habit," occurring as constituents of volcanic rocks ; (3) "adularia" : transparent or milky white crystals, of the habit of Fig. 653, sometimes with narrow B-faces, occurring on the sides of fissures and cavities in metamorphic rocks (gneisses or schists), and very commonly forming twins, or twin groups, on the Baveno law.

The optical characters of orthoclase are somewhat variable ; the negative acute bisectrix always emerges in the plane of symmetry at about 5° above the crystal-axis a, and the extinction with regard to the edge BC is therefore +5° on B, and 0° on C. In adularia and most kinds of orthoclase the axial plane is normal to B and the true angle of the optic axes is about 70°, so that the axes are only slightly inclined to the normals of the prism {110} ; but in some specimens the angle 2V is as great as 85°. In sanidine, however, the axial angle is small (2V usually about 13°), while some crystals are nearly uniaxial and others have their axial plane parallel to B, with a small axial angle.

Descloizeaux found that in sanidine a change of temperature produced a remarkable effect upon the position of the optic axes. For example, a sanidine crystal from the Eifel, for which at 18° C. the value of 2E was 16° (red), with the axial plane perpendicular to B, became uniaxial for red light at 42° C. ; at a higher temperature the optic axes separated out in the vertical plane, so that the plane of the optic axes became parallel to B (010) instead of perpendicular to B, as it was at 18° C. On cooling, these changes are reversed and the axes regain their original directions, unless the crystal has been heated above 600° C., when the change becomes permanent.

Now the various stages of this change are also exemplified by crystals as found in Nature. Some orthoclase (1) has the normal characters of Fig. 651, with the axial plane nearly parallel to C ; some (2) is nearly uniaxial ; some (3) has the axial plane parallel to B. There is generally a well-marked dispersion ; this must be horizontal in Class (1) and inclined in Class (3) (*cf.* p. 179). Most orthoclase possesses the optical characters given in Fig. 651 ; a possible cause of the variations is the pseudo-symmetric structure mentioned on p. 519.

Some orthoclase possesses a pearly opalescence (*e.g.* the Ceylon "moonstone"), and this usually accompanies a parting parallel to the orthopinakoid {100}, or to an ortho-dome near {80$\bar{1}$}, and appears to be due to lamination of different felspathic material, or to inclusions, or to decomposition along planes parallel to that face; it is most conspicuous when (100) is turned towards the observer, and is generally of a pale blue colour.

The colour of orthoclase varies widely, from the colourless glassy sanidine and adularia to the ordinary white, grey, yellow, or flesh-coloured crystals in common granite; most orthoclase is turbid or opaque, owing to partial conversion into kaolin or mica.

Orthoclase often contains a considerable proportion of sodium, which is probably in most cases due to an intermixture of albite (see, however, anorthoclase, p. 520); these varieties are much more fusible than ordinary orthoclase, which melts at about 1150° C.

Some Noteworthy Localities:

Mount Vesuvius.—The ejected blocks of Monte Somma often consist of a pure white granular orthoclase, together with plagioclase, nepheline, and sodalite; in the cavities of this rock are beautiful little glassy plates of sanidine with the usual faces B, *m*, C, *x*, *y*, *o*, *n* (Fig. 651).

Rhenish Prussia.—The sanidinite of the **Laacher See** contains in its cavities large white crystals of the usual tabular habit; sometimes these are red, owing to alteration and staining with iron; they are remarkable for the entire absence of twinning. The masses which contain these crystals seem to be also volcanic ejected blocks. Among the associated minerals are to be noticed nosean, nepheline, biotite, olivine, augite, hornblende.

The neighbouring trachyte of the **Drachenfels** contains large grey porphyritic crystals of tabular sanidine, which are usually Carlsbad twins; they have characteristic vertical streaks on B, due to microscopic cavities. The simple crystals are square prisms (B, C). The crystals are here often broken and the fragments found not far removed from each other, showing that they were formed prior to the consolidation of the rock.

Baveno.—The Baveno quarries in Piedmont furnish fine, flesh-coloured, opaque crystals lining cavities in the red granite with quartz and mica; the crystals are of the Baveno habit, and mostly Baveno twins, triplets, etc., but Carlsbad twins are by no means rare. Fig. 661 is from a photograph of a specimen in the British Museum.

Cornwall.—At many localities in Cornwall the granite contains large porphyritic crystals of orthoclase; Carlsbad twins are very frequent, and the crystals are often wholly or partly converted into white kaolin, so that they are usually opaque, and rough in outline. Large tabular crystals of this kind are found in the kaolinised granite of **St. Austell.** At **Huel Coates** (St. Agnes) pairs of Carlsbad twins sometimes interpenetrate and cross one another at angles which point to twinning upon other laws, *e.g.* with ($\bar{1}$11) and (051) as twin-planes. At this locality the crystals are sometimes completely converted into a brownish granular aggregate of cassiterite and quartz.

Mourne Mountains (County Down).—Druses of the grey granite are lined with sharp crystals of white, opaque orthoclase, of Baveno habit, showing the forms B, C, *m*, *x*, *y*; Carlsbad, Baveno, and also Manebach twins occur. With these are associated smoky quartz and zinnwaldite, and sometimes also topaz and beryl. The white orthoclase has sometimes a peculiar pearly lustre.

St. Gothard. -The granite and gneiss of this district furnish abundant orthoclase, associated with quartz, chlorite, mica, apatite, albite, and hæmatite; especially characteristic are glassy crystals of the adularia

Fig. 661.—Orthoclase on Granite, from Baveno (British Museum).

habit, usually Baveno twins, in which the faces B are covered and partly permeated with powdery chlorite, while C is bright and smooth, with the usual pearly lustre. These crystals are often deeply corroded. The adularia of this and other Swiss localities is often quite opaque and green with enclosed chlorite. When the faces C, *m* are of nearly the same size the adularia crystals resemble rhombohedra; but C may always be recognised by the cleavage; it is striated horizontally.

OTHER FELSPARS ALLIED TO ORTHOCLASE

Microcline is the name given to anorthic potash-felspar. In chemical composition, hardness, specific gravity, and general characters microcline is indistinguishable from orthoclase; a felspar is only referred to microcline when its cleavage-angle, twinning, or optical properties point to the anorthic system. Chief among these characters is the twin-lamellation,

which gives characteristic striæ on the face C; these render the cleavage-angle difficult to determine, since simple untwinned crystals of microcline are almost unknown; BC has been measured as 89° 25′ to 89° 45′, generally about 89° 30′.

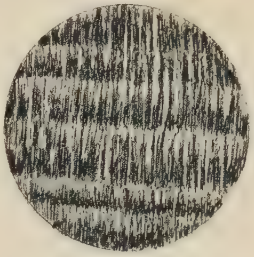


Fig. 662.—Section of Microcline between crossed nicols.

The optical characters are still more difficult to determine, owing to the fact that twinning takes place both according to the albite law (twin-plane, B) and the pericline law (twin-axis, the edge Cx); this divides the crystal into a number of intersecting twin-lamellæ nearly at right angles to each other, and produces a curious rectangular grating-structure or cross-hatching, visible between crossed nicols, and known as the "microcline-structure" (Fig. 662); in sections parallel to the basal plane this generally presents the appearance of two series of tapering lamellæ. So far as they can be ascertained, the optical characters resemble those of orthoclase, except that the extinction on C is not straight but +15° 30′, and the obtuse positive bisectrix is not perpendicular to B but inclined at 15° 26′ to the normal. The axial angle is also larger than in orthoclase, $2V = 84°$.

As pointed out on p. 268, it is possible that microcline and ortho-

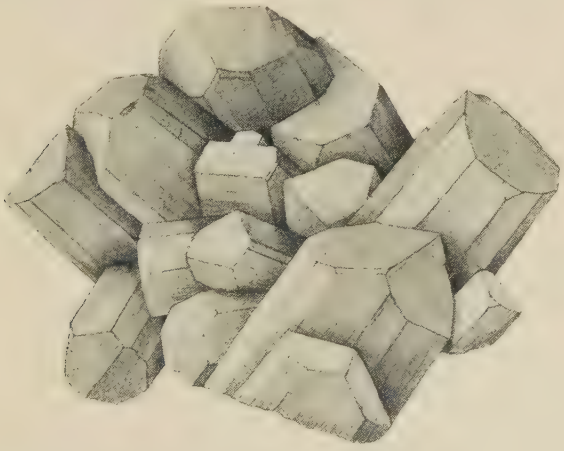


Fig. 663.—Microcline (Amazon-stone) from Pike's Peak, showing C {001}, B {010}, x {$\bar{1}01$}, y {$\bar{2}01$}, m {110}, M {$1\bar{1}0$}, f {130}, z {$1\bar{3}0$}, o {$\bar{1}11$}.

clase may really be identical, the apparently monoclinic symmetry of the latter mineral being due to pseudo-symmetric twinning on so minute a scale as to be invisible under the microscope; if this be so, all the felspars may be in reality anorthic.

The name "amazon-stone" is given to the green varieties of microcline.

Some Noteworthy Localities:

Pike's Peak (Colorado).—In the albitic granite of the Pike's Peak region beautiful large crystals of amazon-stone occur (Fig. 663); these are of the

usual orthoclase habit, and sometimes twinned on the Baveno, Manebach, and Carlsbad laws.

The albitic granite of the **Ilmen Mountains** in Russia has furnished precisely similar light green crystals, and in both localities among the accompanying minerals are smoky quartz, topaz, and glassy rhombohedral crystals of the rare beryllium silicate, phenacite.

Anorthoclase (*ἀν-* not, *ὀρθός*; Germ. *Natronmikroklin*) is a soda-potash-felspar, $(Na,K)AlSi_3O_8$, which resembles microcline in having a cleavage-angle of not quite 90°, and in possessing the cross-hatched structure due to multiple twinning on two laws, but this is sometimes so fine as to be scarcely visible. It is the felspar characteristic of certain groups of alkaline rocks, *e.g.* the lavas of the Island of Pantelleria. In some localities the crystals assume quite a peculiar habit, owing to the predominance of *y* and to elongation along the vertical axis; the "Rhombenporphyr" of Oslo (Christiania) receives its name from the rhombic outlines of the porphyritic crystals of this felspar which it contains (forms *m*, M, *y*). Anorthoclase always contains also a little lime.

Hyalophane (*ὕαλος*, glass, *φαίνω*), remarkable as a barium-felspar, is a monoclinic mineral found in little glassy crystals of adularia habit (*mx*C), like Fig. 653, in the white dolomite of the Binnenthal, which has already been mentioned as a locality for blende and other minerals. The crystals occur in cavities of the dolomite associated with barytes, realgar, pyrites, and other metallic sulphides and sulpharsenites.

Hyalophane contains both barium and potassium and has been shown to be a mixture of orthoclase with a barium silicate, $BaAl_2Si_2O_8$, similar to anorthite, the mixtures corresponding exactly to those of albite and anorthite in the group of plagioclase felspars, which we have next to consider. The crystals are frequently zoned, and show extinction-angles ($a\alpha$) on B varying from $-19°$ in the centre to $+4°$ in the outer layers. The specific gravities vary correspondingly from 2·82 to 2·66.

The pure barium-felspar, $BaAl_2Si_2O_8$, has also been found as a contact mineral in dolomite at Jakobsberg in Sweden, and is known as **celsian**. It is also monoclinic, and has a specific gravity of 3·384 and an extinction-angle ($a\gamma$) on B of $+28°$.

In the Binnenthal crystals of hyalophane the proportion of celsian to orthoclase varies up to the composition Or_2Ce (BaO = 16·4 per cent).

THE PLAGIOCLASE FELSPARS

Albite, Anorthite, and their Mixtures

Albite.—$NaAlSi_3O_8$; $Na_2O = 11·8$, $Al_2O_3 = 19·4$, $SiO_2 = 68·8$.
Anorthic; symmetry, holosymmetric.

$a : b : c = 0·6335 : 1 : 0·5577$. $\alpha = 94° 3'$, $\beta = 116° 29'$, $\gamma = 88° 9'$.

B = {010}, C = {001}, m = {110}, M = {1$\bar{1}$0},
x = {10$\bar{1}$}, y = {20$\bar{1}$}, o = {11$\bar{1}$}, f = {130}, z = {1$\bar{3}$0}.

BC (010) : (001) = 86° 24′, Bm (010) : (110) = 60° 26′, mM (110) : (1$\bar{1}$0) = 59° 14′, Cm (001) : (110) = 65° 17′, CM (001) : (1$\bar{1}$0) = 69° 10′, Bo (010) : (11$\bar{1}$) = 66° 18′, Cx (001) : ($\bar{1}$01) = 52° 16′, Cy (001) : ($\bar{2}$01) = 82° 7′.

Common twins on plane B (010) (albite law). Cleavage C, perfect; B, m, imperfect. Brittle. Fracture, uneven. H = 6; G = 2·624. Colourless. Streak, white. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}539$, $\beta = 1{\cdot}533$. Birefringence, positive, weak; $\gamma - \alpha = 0{\cdot}010$. Acute bisectrix in the zone BC inclined at 15° 36′ to the normal of B, and at 102° to the normal of C. Obtuse bisectrix inclined at 70° to the normal of C; 2V = 81°. $\rho < v$. Fusible (4). Insoluble in acids.

With the above description compare crystals from **Schmirn** (Tyrol).

Albite, as is signified by the name, usually occurs in white crystals, and the best are found lining cavities in granite or in gneiss and the crystalline schists. Albitic granite is the source of many rare and interesting minerals, and the presence of albite is often an indication that such minerals may be found; *e.g.* the topaz and beryl of the Mourne Mountains;

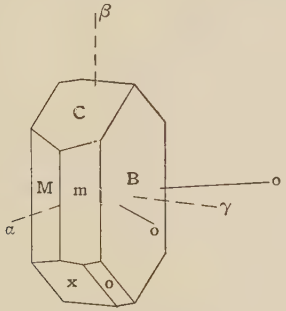


Fig. 664.—Albite, B {010}, C {001}, m {110}, M {1$\bar{1}$0}, x {10$\bar{1}$}, o {11$\bar{1}$}.

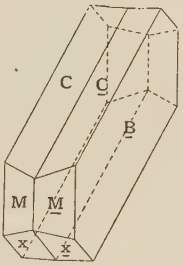


Fig. 665.—Albite twinned on (010) (Albite Law).

the phenacite and topaz of Pike's Peak and the Ilmen Mountains; the topaz, tourmaline, etc., of the Urals.

Ordinary albite is, like Fig. 664, tabular parallel to B; the crystals are usually elongated along the edge Bx. In other cases B is small and the crystals are elongated along the edge Cx (the axis b); the crystals are then called "pericline"; this name ($\pi\epsilon\rho\iota\kappa\lambda\iota\nu\acute{\eta}\varsigma$ = sloping on all sides) was given in allusion to the oblique aspect of the crystals (Figs. 667, 668). As in orthoclase, the face B is vertically striated.

Twinning on B (Fig. 665) is so common in albite that this, the characteristic twin-law of plagioclase, is known as the albite law; the faces C, easily recognised by their pearly lustre, make an angle (generally re-entrant at the exposed end of the crystal) of 7° 12′. Few specimens of albite fail to show this twinning, and it is often repeated as a lamellation (Figs. 253, 254, p. 104).

Pericline is usually twinned according to a different law, the so-called "pericline law"; two individuals having contact along a plane in the zone Cx somewhat inclined to C are related to each other, not by reflection over this plane, but by hemitropy about the edge Cx [010]. Since, in the

anorthic system, the face B is not at right angles to this edge, the faces B, $\underline{B}$, in such a twin do not fall into one plane (Fig. 666), and the line in which they would intersect is not parallel to the edge CB, but makes a considerable angle (22°) with it, as shown in Fig. 667. Twinning of this kind also is frequently repeated, and gives rise to a lamellation (though less often in pure albite than in the larger and less perfectly developed crystals of some of the other plagioclase felspars found in rocks, which show the lamellation clearly on cleavage-surfaces B). In such cases the plane of the lamellæ, *i.e.* the plane of composition of the twins, passes through the line of intersection of the faces B, $\underline{B}$ and through the lines in which the faces $m\underline{M}$ and $M\underline{m}$ meet uniformly, as in Fig. 667. It can be shown that this plane intersects the faces m, M in a rhomb whose acute angles are bisected by the twin axis [010] and truncated by the

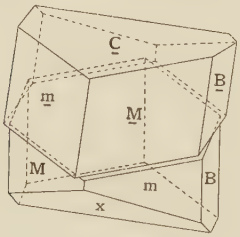


Fig. 666.—Albite twinned on axis [010] (Pericline Law).

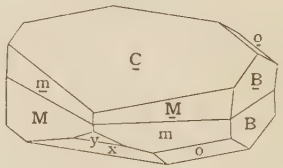


Fig. 667.—Albite twinned on axis [010] (Pericline Law).

edge B $\underline{B}$. Hence it is known as the "plane of rhombic section" (see below, p. 525).

Twinning on the Carlsbad, Baveno, and Manebach laws also occurs in albite, but far more rarely than in orthoclase.

In fusibility, refractive index, and hardness, albite somewhat closely resembles orthoclase, from which, however, it is readily distinguished by its higher specific gravity, as shown by means of a heavy liquid.

In composition albite is entirely analogous to orthoclase, and the two minerals exhibit very close relationships; parallel growths of albite on orthoclase and of orthoclase on albite occur at several localities (see Fig. 406, p. 266); in these the prism-zones coincide, and the faces B, m, M are approximately parallel to each other. Still more intimate associations occur; at Perth in Ontario a red felspar was found, which was described in 1843 as a soda-orthoclase, under the name "perthite." This was subsequently shown to be a parallel intergrowth, in which the laminæ of albite are parallel to the ortho-pinakoid {100} of the orthoclase; many other such intergrowths are now known, the finer varieties being distinguished as "microperthite" or "cryptoperthite," and they finally pass into anorthoclase.

From Canada also (Bathurst) comes "peristerite," an opalescent white albite corresponding to the moonstone of Ceylon; it possesses the same bluish sheen when viewed towards the ortho-pinakoid; the name is given in allusion to the colour, from περιστερά, a dove.

Some Noteworthy Localities :

Mount Scopi (Switzerland).—A white micaceous gneiss has its cavities copiously lined with crystals of pericline. These are usually covered with, or partly permeated by chlorite, and accompanied by titanite, adularia, axinite, and apatite, and are the usual pericline twins. The twin-groups are sometimes triplets or quartets united on the pericline law, and may also contain laminæ parallel to B twinned on the albite law. Here and in the Maderanerthal small crystals of adularia are sometimes situated in parallel position on the pericline.

Very similar specimens are found in the gneiss and mica-schist at **Viesch, Zermatt,** and elsewhere in Canton Wallis (Fig. 668), and come

Fig. 668.—Albite (Pericline) from Zermatt.

also from the **Zillerthal, Pfitsch,** and other localities in the Tyrol. Some of the best colourless albite crystals have been found with calcite, lining druses in the limestone of **Schmirn** (Tyrol).

Tintagel (Cornwall).—The cracks of a silky slate are lined with albite and quartz together with calcite ; the albite (B, C, *m*, M, *o*, *n*, *x*, *y*, etc.) is almost always twinned on B ; fine hairlike crystals of rutile (sagenite) also occur on the specimens.

Anorthite.—$CaAl_2Si_2O_8$; $CaO = 20{\cdot}2$, $Al_2O_3 = 36{\cdot}6$, $SiO_2 = 43{\cdot}2$.
Anorthic ; symmetry, holosymmetric.

$$a : b : c = 0{\cdot}6347 : 1 : 0{\cdot}5501. \quad \alpha = 93^\circ\ 13', \beta = 115^\circ\ 55', \gamma = 91^\circ\ 12'.$$

$$B = \{010\},\ C = \{001\},\ A = \{100\},\ m = \{110\},\ M = \{1\bar{1}0\},$$
$$x = \{10\bar{1}\},\ y = \{20\bar{1}\},\ o = \{11\bar{1}\},\ v = \{24\bar{1}\},\ f = \{130\},\ n = \{0\bar{2}1\},\ e = \{021\},$$
$$k = \{0\bar{2}3\},\ \alpha = \{1\bar{1}1\},\ m' = \{111\},\ t = \{201\}.$$

BC (010) : (001) = 85° 50′, B*m* (010) : (110) = 58° 4′, *m*M (110) : (1$\bar{1}$0) = 59° 29′,
C*m* (001) : (110) = 65° 53′, CM (001) : (1$\bar{1}$0) = 69° 20′, CA (001) : (100) = 63° 57′,
C*x* (001) : ($\bar{1}$01) = 51° 26′, C*y* (001) : ($\bar{2}$01) = 81° 14′, C*e* (001) : (021) = 42° 38′.

Twinned on edge [001] (Carlsbad law), on face (010) (albite law), on face (021) (Baveno law), on face (001) (Manebach law). Cleavage C, perfect ; B, less perfect. Brittle. Fracture, conchoidal. H = 6½ ; G = 2·758. Colourless. Streak, colourless. Lustre, vitreous. Transparent ; $\beta = 1{\cdot}584$, $\alpha = 1{\cdot}575$. Birefringence, weak, negative ; $\gamma - \alpha = 0{\cdot}013$. Obtuse bisectrix perpendicular to *e*. Acute bisectrix inclined (within the crystal) at 53° 14′ to normal of C (001), at 58° to normal of

B (010), at 16° 52′ to normal of o (11$\bar{1}$); 2V = 77°; $\rho < v$. Fusible with difficulty (5). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from **Vesuvius.**

Pure **anorthite** (ἀν- not, ὀρθός) is a rare mineral; the beautiful glassy crystals from Vesuvius contain very small proportions of soda and potash, and the crystallographic and optical data are derived from their study. Fig. 669 illustrates the rich combination of forms on these crystals, in which also twinning has been observed according to the albite, pericline, Carlsbad, and Manebach laws. The habit of the crystals is very varied. The B-faces are not so markedly striated as in orthoclase and albite. The less ready fusibility and the more ready action of acids distinguish anorthite from these minerals. As explained on p. 264 and below, observation in parallel and convergent light of cleavage-flakes parallel to C and B serves to distinguish these three principal felspars from each other.

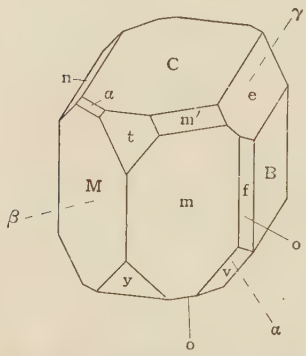


Fig. 669.—Anorthite, from Vesuvius, B {010}, C {001}, m {110}, M {1$\bar{1}$0}, f {130}, t {201}, m' {111}, α {1$\bar{1}$1}, e {021}, n {0$\bar{2}$1}, y {20$\bar{1}$}, v {24$\bar{1}$}.

Some Noteworthy Localities:

Mount Vesuvius.—Limpid glassy crystals occur in cavities of the ejected blocks of Monte Somma (Fig. 669); in the limestone blocks they are accompanied by mica, in the augitic blocks by leucite (glassy), spinel (dark octahedra), meionite (glassy square prisms).

Japan.—In the basalt of **Miyake Island,** large, white opaque, porphyritic crystals, covered with a black crust; forms C, B, y, m, M; frequently Carlsbad twins.

The Intermediate Plagioclases—Oligoclase to Bytownite:

The various soda-lime-felspars are, for the most part, less perfectly crystallised than albite and anorthite, and many of them are chiefly known as rock-constituents, either massive, porphyritic, or microscopic, but usually without well-defined faces. Now that the law of their composition as isomorphous mixtures of albite and anorthite is established, the composition of any specimen and its place in the series may be determined from its specific gravity and the optical examination of cleavage-flakes C and B, as described on pp. 263-265. The following table summarises the essential data for albite and anorthite—the two ends of the series—and for five intermediate mixtures whose compositions are given. The numbers in any column being plotted out as a curve according to the composition, the value for any other intermediate plagioclase of known composition may be found from its place on the curve.

For practical purposes the extinction-angles on the cleavages C and B are most convenient, and are sufficient, but the twinning sometimes renders their determination difficult.

	Sp. Gr.	SiO_2 %	Extinction on C	Extinction on B	β	Visible through B (Inclination to Normal)	Angle of Rhombic Section
Orthoclase . .	2·56	64·8	0° 0′	+5°	1·523	+bis. (0° 0′)	
Microcline . .	2·56	64·8	+15° 30′	+5°	1·523	+bis. (15° 20′)	
Albite . Ab	2·624	68·8	+ 4° 30′	+19°	1·533	+bis. (15° 36′)	+22°
Oligoclase Ab_6An	2·645	64·7	+ 2° 45′	+12°	1·539		+10°
Andesine . Ab_3An	2·659	61·7	+ 1° 4′	+ 4° 36′	1·546		+ 3°
Labradorite $AbAn$	2·694	55·0	− 5° 10′	−16°	1·558		− 1°
Bytownite $AbAn_3$	2·728	48·5	−17° 40′	−29° 28′	1·570		− 9°
$AbAn_6$	2·742	45·8	−27° 33′	−33° 29′			−20°
Anorthite . An	2·758	43·2	−37°	−36°	1·584	opt. ax. (43° 12′)	−16°

For quartz, specific gravity = 2·653 ; $\omega = 1{\cdot}544$; $\epsilon = 1{\cdot}553$.

The last column gives the angle between the edge CB and the line of union on the face B between the individuals of a pericline twin. This angle depends upon the angles of the crystal and especially upon the angle (γ) between the edges Cx and CB.

Fig. 670 shows the position of the rhombic section in albite, Fig. 671 in anorthite. The trace of this plane on B makes an angle of +22° with the edge BC in albite, and −16° in anorthite (the terms + and − being

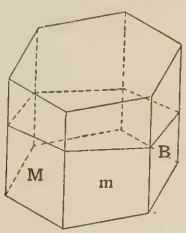


Fig. 670.—Albite, Rhombic Section.

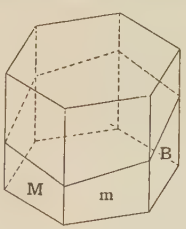


Fig. 671.—Anorthite Rhombic Section.

used in the same sense as for the extinctions on B (*cf.* Fig. 404). For the intermediate plagioclases the angle has intermediate values.

The directions of the bisectrices and optic axes can be understood from Fig. 405 (p. 263) ; as we pass down the series from albite to anorthite the positive bisectrix travels from γ_{Ab} to γ_{An}, and the negative bisectrix from α_{Ab} to α_{An} ; the angle 2V is large, and varies from about 77° in albite to 103° in anorthite (about the positive bisectrix). The interference-figures yielded in convergent light by cleavage-flakes B of albite, and B and C of labradorite and anorthite, are shown in Figs. 672 to 676.

The mean refractive index β (*cf.* column 6), may be approximately determined by immersion in liquids of known refractive index, or

sometimes in rock sections (when the felspar is in contact with balsam or with a crystal of quartz), by Becke's method, described on p. 324. The refractive indices of quartz (ω) and balsam lie between those of oligoclase and andesine; it is therefore not difficult to say whether the felspar belongs to the more acid plagioclases, oligoclase or albite, or the more basic ones lying below these in the table.

The comparative readiness with which they yield to acids also distinguishes the basic from the acid plagioclases; on the other hand, the latter are the more fusible.

Chemical tests are not often used to distinguish the various members

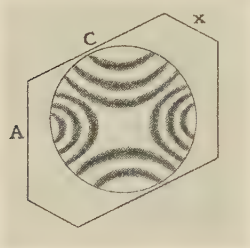


Fig. 672.—Albite, Cleavage B (010).

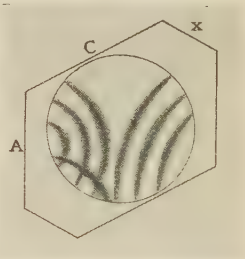


Fig. 673.—Labradorite, Cleavage B (010).

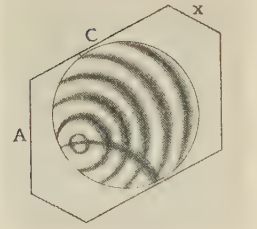


Fig. 674.—Anorthite, Cleavage B (010).

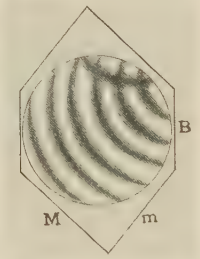


Fig. 675.—Labradorite, Cleavage C (001).

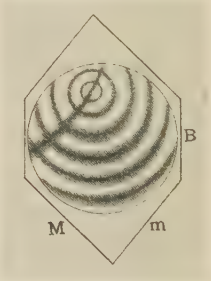


Fig. 676.—Anorthite, Cleavage C (001).

of the series, which generally contain not only soda and lime but also a little potash. Careful comparative tests of the flame colour imparted to a Bunsen burner (Szabo's flame test) yield a sufficiently reliable estimate of the relative proportions of soda and lime to place a plagioclase approximately in its position in the series; a qualitative examination for calcium is also useful as a confirmatory test. The presence of potash in small quantities in most plagioclases suggests that they may also contain an isomorphous admixture of a potash-felspar (microcline, anorthoclase, or orthoclase). Zonal growths of one felspar upon another are very common in rocks; sometimes in a section these may be discerned as regular bands surrounding a nucleus, the extinctions in successive bands being different. Where the composition gradually changes from the nucleus to the exterior, the crystal, as a whole, does not possess a definite ex-

tinction, but a wave of shadow passes over it inwards or outwards as the section is rotated between crossed nicols. In such cases the inner and older portions are usually more basic than the outer and later layers.

The following are typical examples of a few of the most conspicuous plagioclases :

Oligoclase.—At **Arendal** in Norway, veins in the granite contain large yellowish crystals of oligoclase with orthoclase, quartz, epidote, garnet, and calcite. They are generally of pericline habit and pericline twins, but sometimes present much the appearance of orthoclase ; the positive inclination of the rhombic section shows that they belong to the albite end of the series. The mineral has a composition between Ab_4An and Ab_6An.

At Tvedestrand, not far from Arendal, in gneiss, are found reddish cleavable masses of the mineral known as " sunstone." This is a beautiful " avanturine " (or spangled) felspar with a golden shimmer or sparkle which appears to be due to enclosed scales of hæmatite or göthite. The plagioclase striation on C can usually be seen, and the small inclination of the rhombic section can sometimes be made out on B. The mineral has nearly the composition Ab_3An.

Andesine.—At **Bodenmais** in Bavaria the remarkable rock of the Silberberg consists in part of a dark green, somewhat greasy, felspar associated with magnetite, biotite, pyrrhotite, chalcopyrite, quartz, etc. This felspar is partly orthoclase, but partly a mineral exhibiting the plagioclase striation, and sometimes a microcline structure. The specific gravity, 2·68, and composition ($SiO_2 = 58$ per cent), of such specimens justifies their reference to andesine, but the mineral is so mixed with orthoclase, and other felspar, that the determination is difficult.

It will be seen on referring to the table on p. 528 that some varieties of andesine or oligoclase-andesine may be easily mistaken for orthoclase, for the extinction on C and B may be about 0° and +5°, respectively. In such a felspar, however, the specific gravity will be higher than that of orthoclase, and nearly equal to that of quartz.

Labradorite.—On the coast of **Labrador** occur masses of a rock consisting mainly of hypersthene and labradorite. Both minerals may be beautifully opalescent, and the specimens, much used for decorative purposes, are known as " labrador spar." The labradorite is found in quite large masses and shows a magnificent change of colours (p. 318), generally blue, but also green, yellow, or red ; the twin-lamellæ (generally on the albite law) being often very conspicuous as bands of different colour. The opalescent colour is caused by the interference of light reflected from thin lamellar inclusions. It has recently been shown by Lord Rayleigh that two distinct sets of these are present : (1) small rectangular plates of various minerals (visible with a lens) lying parallel to B, and (2) extremely minute and thin irregular patches (possibly fissures), about 0·005 mm. in diameter, arranged parallel to a plane inclined at about 15° to B. Each set of inclusions gives rise to a coloured reflection, but that caused by the finer plates is the more conspicuous. It is difficult to determine the characters of the felspar with certainty, but the specific gravity (up to

2·7), the extinction-angles (−5° and −17°), and the composition (SiO_2 = 54 to 56 per cent) indicate that the mineral possesses nearly the constitution AbAn, and belongs to the andesine end of the labradorite section.

Bytownite.—Well-defined crystals of the most basic plagioclases are rare; they mostly occur as constituents of basalts, gabbros, and other basic rocks. The name was originally given to the felspar of a rock from **Bytown** in Canada, which, however, ultimately proved to be a mixture of anorthite with quartz and other minerals.

In view of the importance of the felspars as essential constituents of most igneous rocks, the determination of the nature of the felspar present, by the examination of a thin section of the rock under the microscope, is one of the most important problems of petrology, and many more or less elaborate methods have been devised for this purpose. Such sections usually contain a large number of small crystals of the felspar, cut in different (and unknown) directions, and from these suitable sections must first be selected before the methods above described, such as the determination of extinction-angles and observation of interference-figures, can be applied.

One of the simplest methods depends on the fact that the rock-forming felspars usually form lath-shaped crystals, elongated along the edge BC (Baveno habit). Sections in the zone BC can then be recognised by their elongated shape; and if a number of such sections of a given felspar be examined, they will be found to show different extinction-angles varying up to a maximum value. If, then, the maximum extinction-angle for such sections in a slide be measured the felspar can be recognised. (See the table below.)

Another method is based on the fact that in the almost universally present albite twins the crystals are symmetrical on either side of the twin-plane (B). Hence, in any section perpendicular to this plane, the extinction-angles on the two halves will be equal and in opposite directions, and such sections can be recognised by this character. The extinction-angle varies in different sections but does not exceed a maximum value.

The subjoined table shows the maximum extinction-angles (measured between the edge BC and the *less* strongly refracted vibration) for different plagioclase felspars: (1) on sections in the zone BC, and (2) on sections perpendicular to B.

	Maximum Extinction-angle	
	On Sections in Zone BC.	On Sections ⊥ B.
Ab	+20°	−16°
Ab_6An	+ 7°	− 8°
Ab_3An	0°	+ 7°
Ab An	−18°	+28°
Ab An_3	−50°	+44°
Ab An_6	−56°	+52°
An	−64°	90°

SECTION XXI

SILICATES CONTAINING HALOGENS

THE MICA GROUP

Mica (Germ. *Glimmer*). —The micas are of very common occurrence as constituents of granites, gneisses, and schists, and some varieties are largely worked for commercial purposes, for the manufacture of lamp chimneys, for electrical insulation, etc. They crystallise in forms which are nearly hexagonal, and possess a highly perfect basal cleavage.

In reality a large number of different, though, no doubt, closely related minerals, are included under the name mica. They are all silicates of aluminium and of either K, Na, Li (the alkali-micas), or of Fe, Mg (the ferro-magnesian micas), generally containing water of constitution (*i.e.* H or OH), and in some cases also fluorine.

The best defined crystals are those of the ferro-magnesian mica, biotite, which are found as glistening green, black, or brown crystals in the ejected blocks of Monte Somma (Mount Vesuvius), together with other well-crystallised minerals. These we may take as a type of the micas, and to them the following description applies.

Biotite. — Silicate of aluminium, magnesium, iron, and potassium. A typical analysis gave $SiO_2 = 39{\cdot}30$, $Al_2O_3 = 16{\cdot}95$, $Fe_2O_3 = 7{\cdot}86$, $MgO = 21{\cdot}89$, $K_2O = 7{\cdot}64$, $H_2O = 4{\cdot}02$, $F = 0{\cdot}89$, together with a little FeO, MnO, CaO, and Na_2O, corresponding (only approximately) to $K_2HMg_6Al_3(SiO_4)_6$.

Monoclinic.

$$a : b : c = 0{\cdot}577 : 1 : 3{\cdot}274. \quad \beta = 90° \ 0'.$$

$$M = \{221\},\ B = \{010\},\ C = \{001\},\ \mu = \{11\bar{1}\}.$$

$$\mu\mu\ (11\bar{1}) : (1\bar{1}\bar{1}) = 59° \ 14',\ C\mu\ (001) : (\bar{1}11) = 81° \ 19',\ MM\ (221) : (2\bar{2}1) = 59° \ 48',$$
$$CM\ (001) : (221) = 85° \ 38';\ (110) : (1\bar{1}0) = 60° \ 0'.$$

Twins ; twin-plane parallel to (110) ; plane of composition C. Cleavage C, very perfect. Laminæ elastic (see p. 313). Fracture, uneven. $H = 2\frac{1}{2}$; $G = 2{\cdot}86$. Plane of optic axes parallel to B ; acute bisectrix inclined at 0° 30′ to normal of C. $\beta = 1{\cdot}60$, $\alpha = 1{\cdot}56$. Birefringence, negative, strong ; $\gamma - \alpha = 0{\cdot}04$; $\rho < v$; $2E = 12° \ 48'$ for yellow, 12° 22′ for red. Pleochroic, α yellow or green, β and γ dark brown. Translucent. Colour, dark green. Lustre, vitreous. Streak, colourless. Fusible with difficulty. Decomposed by sulphuric acid, leaving a skeleton of silica.

With the above description compare crystals from **Vesuvius**.

The chief micas are generally separated under the following names:

Muscovite (Potash-mica).—$SiO_2 = 42$ to 55, $Al_2O_3 = 20$ to 38, $K_2O = 8$ to 12, $H_2O = 2$ to 6. Axial plane perpendicular to plane of symmetry (Fig. 677). $2E = 56°$ to $76°$; $\rho > v$.

Muscovite (so named as having been first obtained from Russia) is the commonest mica, and the variety usually contained in granites and mica-schists; it is generally a pale-coloured, sometimes colourless, mineral with pearly lustre on the cleavage-surface; it occurs generally, like all the other micas, in hexagonal scales or plates—but sometimes in long tapering

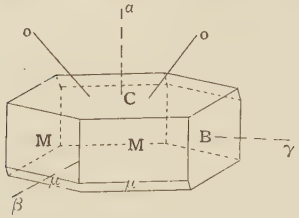


Fig. 677.—Muscovite, C {001}, B {010}, M {221}, μ {11$\bar{1}$}.

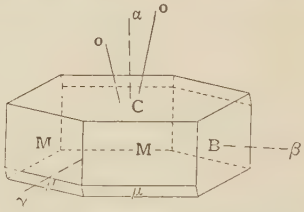


Fig. 678.—Phlogopite, C {001}, B {010}, M {221}, μ {11$\bar{1}$}.

crystals with rough and irregular side faces, of the habit shown in Fig. 681, always, of course, tending to split across their length.

Paragonite (Soda-mica).—$SiO_2 = 44$ to 50, $Al_2O_3 = 36$ to 40, $Na_2O = 4$ to 8, $H_2O = 2$ to 5. Axial plane perpendicular to plane of symmetry. $2E = 70°$ about; $\rho > v$.

Paragonite was the name given to the white schist in which staurolite and cyanite are found at Monte Campione in Switzerland; the rock was originally supposed to be a talc-schist until analysis showed it to be a soda-alumina and not a magnesia silicate. The name ($\pi\alpha\rho\acute{\alpha}\gamma\omega$, I mislead) was given in allusion to this fact.

Lepidolite (Lithia-mica).—$SiO_2 = 49$ to 52, $Al_2O_3 = 26$ to 33, $Li_2O = 4$ to 6, $K_2O = 4$ to 10, $F = 3$ to 8. Axial plane usually perpendicular (occasionally parallel) to plane of symmetry. $2E = 50°$ to $84°$; $\rho > v$.

Lepidolite is a rose-coloured or lilac mineral usually found in granular scaly aggregates; the name is derived from $\lambda\epsilon\pi\acute{\iota}\varsigma$, a scale; the colour is probably due to manganese.

Zinnwaldite (Lithia-iron-mica).—$SiO_2 = 43$ to 46, $Al_2O_3 = 20$ to 22, $K_2O = 5$ to 10, $Li_2O = 1$ to 4, $F = 5$ to 8. Axial plane parallel to plane of symmetry. $2E = 50°$ to $70°$; $\rho < v$.

Zinnwaldite was the name applied to the mica of the tin-bearing veins of Zinnwald in Bohemia, and it has generally been found that these lithia-iron-micas occur in pegmatitic veins in granites and gneisses, and especially in those which produce cassiterite associated with fluor.

Phlogopite (Magnesia-mica).—$SiO_2 = 40$ to 45, $Al_2O_3 = 11$ to 17, $MgO = 26$ to 29, $K_2O = 7$ to 10. Axial plane parallel to plane of symmetry (Fig. 678). $2E = 0°$ to $20°$; $\rho < v$.

Phlogopite includes the yellow and brown micas, which are, like muscovite, sometimes found in rough prisms or tapering pyramids; like muscovite also showing a pearly lustre upon the cleavage-face. The mineral is found in metamorphic limestones, sometimes in quite large crystals. It is impossible to draw a sharp distinction between phlogopite and biotite. The name was given in allusion to the red-brown colour (*φλογωπός*, fiery looking).

Biotite (Magnesia-iron-mica).—SiO_2 33 to 40, Al_2O_3 = 16 to 24, $Fe_2O_3 + FeO$ = 10 to 30, MgO = 7 to 22, K_2O = 1 to 10, H_2O = 1 to 5. Axial plane usually parallel (occasionally perpendicular) to plane of symmetry. $2E = 0°$ to $20°$; $\rho < v$.

Biotite may, in fact, be regarded as a ferriferous phlogopite; it includes the dark-coloured micas, which are often found, sometimes together with the white muscovite, as a constituent of granite, and occurs very commonly in eruptive rocks and in crystalline schists. Some of the biotites have an almost inappreciable axial angle, and the name was originally given to all the magnesia micas in honour of Biot, who (in 1816) found them to be uniaxial. Varieties containing a large proportion (8 to 27 per cent) of Fe_2O_3 are distinguished as "lepidomelane."

The micas all crystallise in the monoclinic system with angles which nearly correspond to hexagonal symmetry; they have the form of hexa-

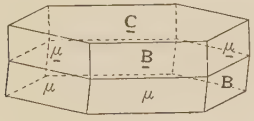


Fig. 679.—Biotite twinned on (110).

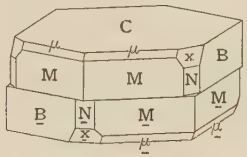


Fig. 680.—Muscovite twinned on (110).

gonal tables or columns, whose prism-angle is nearly 60°, although the prism-faces are slightly inclined to the base. It might appear more natural to take the prominent prism M of Fig. 677 as {110}, and some authors do so; the prism M is here taken as {221}, because with this notation (110) is a face in the zone CM exactly perpendicular to C, so that the crystal can be referred to three rectangular axes; further, this plane (110) is the common twin-plane of the micas, although it is not found as a crystal-face. The upper edge CM of Fig. 677 is sometimes replaced by facets of *o* {112} ($Co = 73° 1'$).

In the twin-crystals one individual usually lies upon another, the faces C being in contact (Figs. 679 and 680); the twin-plane is parallel to a plane of {110}, which replaces the edge Mμ and is perpendicular to C.[1] Fig. 679 is biotite from Vesuvius. Fig. 680 represents a little brown crystal of muscovite from the Sulzbachthal in Salzburg; here N = {261}, $x = \{13\bar{1}\}$. In Fig. 679 the lower crystal, and in Fig. 680 the upper crystal, is in the

[1] This is the customary way of describing the twins of mica, the relation between the crystals being expressible by reflection over a plane of {110} or by hemitropy in that plane. The latter may also be described as hemitropy about an edge C*x* ($x = \{13\bar{1}\}$), which is perpendicular to the above plane. As {110} does not occur as a face of the crystal this way is perhaps the more natural one.

normal position, *i.e.* with its plane of symmetry (and the B-face) running from front to back. The twin-plane truncates the edge $\mu\underline{\mu}$ or $M\underline{M}$; the twinning may be recognised by the re-entrant angles between the two individuals. $B\underline{\mu} = 8° 41'$, $\mu\underline{\mu} = 17° 22'$. As compared with Fig. 677 these crystals have been turned over about the *a*-axis, and this position is adopted by some authors for mica; μ then becomes $\{111\}$, M $\{22\bar{1}\}$, N $\{26\bar{1}\}$, and x $\{131\}$; if the vertical axis *c* is then halved, as is done by others, the indices are: $\mu = \{221\}$, $M = \{44\bar{1}\}$, and $a : b : c = 0{\cdot}577 : 1 : 1{\cdot}637$.

Owing to twinning, and the rough character of the pyramid faces, most large crystals of mica are rude prisms tapering to one end with very irregular sides (Fig. 681); but owing to its very ready cleavage the mineral is generally found in irregular plates and scales or cleavage-flakes.

The crystals sometimes attain large dimensions, and may even measure several feet across, as in the mica of India, Russia, and the United States, used for commercial purposes. All the minerals of this group resemble each other and are distinguished from other minerals by the highly perfect basal cleavage, which permits of their separation into perfectly smooth plates and films of extreme thinness (a property utilised to produce the $\frac{1}{4}$-wave-length mica plate, p. 191), and also by their "elasticity" (see p. 313), so that cleavage-flakes are not pliable, like those of gypsum, but spring back after being bent.

Some of the micas are nearly or quite uniaxial, while others are biaxial with a large angle, but they are all alike in the sign and magnitude of their double refraction, which is always negative and strong, while the refractive power is rather weak, and in having the acute bisectrix nearly perpendicular to the cleavage. The coloured micas are strongly pleochroic, the rays which vibrate parallel to the cleavage being far more absorbed than those which vibrate perpendicular to it; hence any section of mica cut across the cleavage appears darkest when its cleavage-lines are parallel to the shorter diagonal of the polarising nicol prism. In rock sections this readily distinguishes a cross-section of mica from a prism of tourmaline, for the latter appears darkest when its prism-edge is parallel to the longer diagonal of the polariser (pp. 198, 199, Figs. 381, 382). Even where there is no visible crystalline contour the monoclinic nature of a mica crystal can be proved by the optical examination of a cleavage-flake; for whether the plate be uniaxial or biaxial the optic axis, or the acute bisectrix, is never rigidly perpendicular to the cleavage-plane, but makes with the normal to that plane an angle which may vary from a few minutes to eight degrees, and lies in the plane of symmetry (parallel to B).

With change of temperature the inclination of the acute bisectrix to the cleavage-plane is found to change slightly, while it remains in the plane of symmetry, and this property enabled Hintze to prove that a very perfect reddish-brown crystal of Vesuvian biotite, the measurements of which made it appear hexagonal or orthorhombic in symmetry, was really monoclinic, since in those systems the optic axis or the acute bisectrix would remain perpendicular to the basal plane at all temperatures, whereas a change of more than 30′ was observed at 178° C.

The position of the plane of symmetry may be found in any cleavage-

plate of biaxial mica by means of the "percussion-figure." This figure, as explained on p. 123, consists of a six-rayed star in which the rays intersect at angles of 60°; one of them (usually better defined than the others) being parallel to (010). Now one of these rays will be found to be perpendicular or parallel to the plane of the optic axes, and therefore parallel to one of the directions of extinction; this particular ray must therefore be the trace of the plane of symmetry. In the first case the cleavage-flake is said to belong to a "mica of the first class" ("macrodiagonal mica"), in the second case to a "mica of the second class" ("brachydiagonal mica").

The figure ("pressure-figure") produced by pressing upon a cleavage-plate with a *blunt* point is a six-rayed star whose rays bisect the angles between those of the percussion-figure and indicate the existence of glide-planes parallel to the faces of various pyramids; these have been referred to the forms $\{\bar{2}05\}$ and $\{135\}$.

The "asterism" which is shown by some micas, and is particularly common in phlogopite, is probably due to fine inclusions arranged along the glide-planes. A spot of light viewed through a cleavage-flake of such mica appears as a six-rayed star; or sometimes as a twelve-rayed star; or may give six or twelve distinct images of the spot. Inclusions of various minerals in mica are very common; they are usually in the form of very thin plates lying parallel with the cleavage of the mica. Even tourmaline (as in the muscovite of Paris in Maine) and garnet (in the muscovite of Haddam, Connecticut) occur thus as transparent flakes or films. Beautiful translucent brown and red dendritic inclusions of hexagonal symmetry occur in the muscovite of Pennsbury (Pennsylvania). These probably consist of hæmatite and göthite.

As regards their chemical composition the micas are extremely various and difficult to classify; there can be little doubt that they will ultimately be referred to certain isomorphous series, like the felspars or the garnets, but at present it is impossible to assign a general formula with any certainty to the whole group or even to any section of the group.

As constituents of rocks they are roughly divided into dark micas and white micas. The dark (ferro-magnesian) micas are generally uniaxial, or nearly so, and are classed together under the name of biotite; the white (potash-) micas are generally biaxial with an apparent angle of about 60°, and are classed together under the name of muscovite.

Some of the dark micas have a composition approximately represented by the formula $(K, H)_2(Mg, Fe)_2Al_2(SiO_4)_3$, in which the oxygen ratio is that of an orthosilicate (1 : 1). Similarly some of the light micas have approximately the composition $KH_2Al_3(SiO_4)_3$. But there are other varieties which cannot be regarded as normal orthosilicates, since in many of them the oxygen ratio (of silica to bases) is greater, and in some cases less, than in an orthosilicate. The water which is contained in the micas is mostly given off at a high temperature, and must be regarded as water of constitution, although in many specimens there may be a certain amount of water held mechanically between the fine cleavage-laminæ, which will be given off at a lower temperature. In what manner the fluorine enters

into the composition of a mica, how the hydrogen is combined, how the excess or deficiency of oxygen above or below the orthosilicate ratio is to be accounted for, and of what silicic acids these minerals are salts, are questions which have not yet been satisfactorily solved.

For ordinary purposes the group is most conveniently divided as above into—

Ferro-magnesian micas—Biotite.
Alkali-micas—Potash-mica—Muscovite.
Soda-mica—Paragonite.
Lithia-mica—Lepidolite.[1]

Besides these, micas which are rich both in lithia and ferrous oxide are distinguished as zinnwaldite; others which contain much magnesia and little iron are known as phlogopite, while others again, with much ferric oxide, are called lepidomelane.

Many attempts have been made to determine compounds of which the various micas may all be regarded as isomorphous mixtures. The best known of these are due to Tschermak (1878) and to F. W. Clarke (1890).

Tschermak's theory of the mica group is as follows:

Normal muscovite ("damourite"), and other alkali-micas in which the proportion Al : Si = 1 : 1, may be represented by a formula $HAlSiO_4$, in which H is replaced vicariously by varying proportions of K or Na. The ferro-magnesian micas can mostly be represented as mixtures of this silicate with different proportions of a magnesium silicate Mg_2SiO_4. The remaining members of the group, in which the oxygen ratio is greater than that of an orthosilicate (particularly the lithia-micas and the phlogopites), may be regarded as mixtures in different proportions of one or both of the above with a hypothetical silicic acid, $H_4Si_5O_{12}$, in which 4(OH) may be replaced by 4F, and 4O by $4F_2$.

The four constituents which form the basis of the whole mica group will then be:

$R'_3Al_3Si_3O_{12}$	K	where— $R' = (H, K, Na, Li)$, $R'' = (Mg, Fe)$, and Al may be partly replaced by Fe'''.
$R''_6Si_3O_{12}$	M	
$H_4Si_5O_{12}$	S	
$Si_5F_{12}O_4$	S′	

The first of these (K) represents normal muscovite and paragonite, and is the main constituent of all other micas. M is a hypothetical polymer of olivine not known to exist alone, but presumably isomorphous with K. The hypothetical compounds S and S′ are assumed in order to explain the composition of the lithia-micas, in some of which the ratio Al : Si approximates to 2 : 3, of phlogopite and of the more acid varieties of muscovite distinguished as "phengite." In most of these micas more or less fluorine is present.

[1] The mineral known as margarite was formerly included by some authors in the mica group. It is, however, a more basic compound than the micas, and finds a place more naturally in the clintonite group (p. 564).

For example, the formula of normal muscovite is $KH_2Al_3Si_3O_{12}$; that of a typical biotite may be $2K_3H_3(Al_3Si_3O_{12})_2 + Mg_6Si_3O_{12}$; and that of a typical lepidolite $3Li_3K_3(Al_3Si_3O_{12})_2 + 2Si_5F_{12}O_4$.

Clarke's theory of the mica group starts from the idea that the natural silicates are probably salts of simple constitution; and he finds that all the micas may be regarded as substitution derivatives of a normal orthosilicate $Al_4(SiO_4)_3$. One, two, or three atoms of Al may be replaced by equivalent proportions of monovalent alkali metals, or by the divalent metals Mg, Fe″, or by Fe‴. In those micas which contain fluorine, the monovalent groups MgF or AlF_2 are supposed to act as replacing radicals; into those in which there is defect of silica the monovalent groups AlO or MgOH are supposed to enter; in those which present an excess of silica the orthosilicic acid H_4SiO_4 is partially replaced by the tetrabasic acid $H_4Si_3O_8$ (*cf.* the felspar group, p. 512).

Hence all the micas may be expressed as isomorphous mixtures of salts varying in composition from $Al_3R'_3(SiO_4)_3$ to $AlR'_9(SiO_4)_3$ and from $Al_3R'_3(Si_3O_8)_3$ to $AlR'_9(Si_3O_8)_3$.

Some of the lepidolites appear to have the composition of simple metasilicates. These would be represented on Clarke's theory as mixtures: $H_4SiO_4 + H_4Si_3O_8 = 4H_2SiO_3$.

Some writers classify the micas according to the presence or absence of fluorine.

These views illustrate the difficulty of determining with certainty the relationship between the different micas, and we shall here be content to classify them by their general composition according to the table on p. 530.

Many authors (following Tschermak) divide them into the two groups: "micas of the first class," in which the optic axial plane is *perpendicular* to the plane of symmetry and $\rho > v$, and "micas of the second class," in which the axial plane is *parallel* to (010) and $\rho < v$. To the first class belong almost all the alkali-micas; to the second class belong the ferromagnesian micas, phlogopite, and zinnwaldite, and some lepidolites. Those anomalous biotites which do not conform to this rule are placed in the first class under the name "anomite." A great convenience of this classification is that it is always possible, by means of the percussion-figure and microscope, to refer any cleavage-flake of mica to one of these two classes.

The micas are of very widespread occurrence. Muscovite is an essential constituent of most granites, and occurs in some of the quartz-porphyries, but is not found in the volcanic lavas; the best specimens in mineral collections are those in which the muscovite forms large platy crystals in the granite or is crystallised out in druses of that rock; it is also found as an important constituent of the crystalline schists, and in many metamorphic rocks, especially where slates and other sedimentary materials have been subjected to regional metamorphism. As regards the other alkali-micas, lepidolite is also found in granites, in pegmatite veins associated with tourmaline and other minerals which contain fluorine; paragonite is comparatively rare, and is almost entirely confined to the crystalline

schists. Zinnwaldite almost always accompanies the tin ore of certain granites, where it is also associated with tourmaline. Biotite is, like muscovite, characteristic of the granites, but also of many volcanic rocks, of the crystalline schists, and of the contact zones between granite and sedimentary rocks, and is also a constituent of the minette of the Vosges. Phlogopite is found in metamorphic crystalline limestones.

The isomorphism of the micas is indicated not only by the close resemblance of their form and cleavage but also by their tendency to grow together in regular positions; thus crystals are common in which a core of biotite is surrounded by and passes into a shell of muscovite. Again, the pink lepidolite, which is found at Schüttenhofen in Bohemia, in a pegmatite traversing limestone, frequently encloses a nucleus of greenish muscovite, the cleavage running right through the compound crystal; the two minerals appear to be generally twinned together; the same zonal growth is also to be found in the very similar occurrence of lepidolite at Auburn (Maine).

Mica was not separated from talc and gypsum (which it only resembles in cleavage) until the end of the eighteenth century. Klaproth (1810) distinguished the magnesia-micas, and they received the name biotite in 1816. The lepidolite from Moravia was early distinguished on account of its colour; the presence of lithium was first proved in 1820.

Heated in the closed tube all the micas yield a little water; lepidolite and zinnwaldite give the red lithium-colour to flame and are readily fusible (2), lepidolite to a grey, and zinnwaldite to a dark globule. Muscovite and paragonite are almost unacted upon by strong boiling sulphuric acid; biotite and phlogopite are partially decomposed; these four minerals are only slightly fusible. Most micas, like other minerals containing F and OH, yield acid water in the closed tube.

Chromium-mica ("fuchsite") may be distinguished by its brilliant green colour. Manganese-mica (*e.g.* the so-called "alurgite" of Piedmont) may be distinguished by its deep red colour.

Some Noteworthy Localities:

Muscovite.—Muscovite occurs in large plates at many places in the albitic granite of the Urals, notably at **Alabaschka** near Mursinka, where it is associated with orthoclase, albite, and smoky quartz.

Very large transparent sheets of muscovite are obtained from **Solovetsk Island** (Archangel).

Thin transparent sheets of this mineral were formerly used largely for window glass in houses and also in the Russian ships of war (as being less liable to break with the concussion of cannon); it was commonly known as "muscovy glass." Large plates for commercial use are now obtained from **Bengal** and from the granite of **Brazil**; it is used for insulating purposes in electric machinery, for lantern glasses, and for lamp chimneys (formerly wrongly called talc); it was formerly known as *glacies Mariae* (or *Frauenglas*), because the scales were used as spangles to decorate statues of the Virgin.

Lepidolite.—Lepidolite is found at **Rozena** (Moravia) in a broad band

at the junction of a pegmatitic vein-granite with a granulitic gneiss on the Hradisko Mountain. The lepidolite occurs as granular scaly masses of a delicate peach-red colour, and is associated with topaz, tourmaline, etc.

This lepidolite is to be found in all collections; it is a very pure lithia-mica containing 5·88 per cent of Li_2O, and is almost the only source of the lithium compounds used for medicinal and other purposes.

The large hexagonal plates of mica found in "vughs" or druses of many of the tin-bearing granites of **Cornwall** are to be referred to this species or to zinnwaldite. A typical lepidolite in silvery plates, associated with quartz, topaz, and cassiterite, is found in the granite of **St. Michael's Mount** (Marazion).

Phlogopite.—In the granular white dolomite of **Campolongo** (Ct. Tessin, Switzerland), associated with greenish tourmaline, is found a typical phlogopite, which occurs in pale yellowish-brown lustrous scales and hexagonal plates.

Phlogopite occurs at **Oxbow** (Jefferson County, New York) (Fig. 681), in a white crystalline calcite which is mixed with abundant greenish serpentine. The phlogopite is in plates or long rude crystals which are of a light reddish-brown colour on their cleavage-surfaces. In other parts of New York and in Canada (*e.g.* at **Burgess,** Ontario) a similar phlogopite is found, also in granular calcite associated with serpentine.

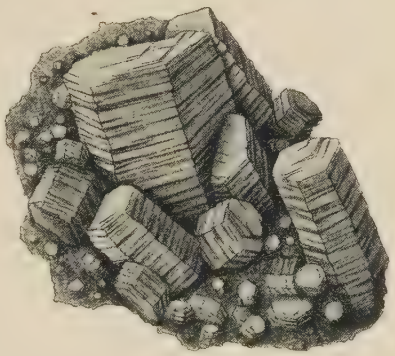


Fig. 681.—Phlogopite from New York.

Biotite.—The best crystallised examples of mica to be found are those which occur in the druses of the limestone blocks ejected from **Monte Somma** (Vesuvius). This, which is known by the name of "meroxene," is a variety of biotite, being a potash-magnesia-mica containing about 7 per cent of FeO. The brilliant little crystals in the druses vary from colourless to green, yellow, brown, black, or red; they may be either thin plates, thick tables, or long tapering prisms, and their prism and pyramid faces are often perfectly smooth and lustrous. Accompanied by brilliant crystals of augite, olivine, humite, etc., they constitute very beautiful specimens, and are to be found in most collections.

The sanidine bombs of Monte Somma also contain scaly aggregates of a dark-coloured biotite.

Biotite is found in enormous dark brown sheets in a coarsely granular calcite on the **River Sludianka** near Lake Baikal (Siberia). This mica is the typical anomite of Tschermak, being a biotite which belongs to the first class, having its axial plane perpendicular to the plane of symmetry.

Zinnwaldite.—In the stanniferous lodes which traverse a coarsely granular greisen at **Zinnwald** (Bohemia) are found hexagonal plates, sometimes of considerable size, of a grey (to green, brown, or yellow) zinn-

waldite, accompanied by fluor and cassiterite, and sometimes scheelite. The mica is generally crystallised upon quartz, and the plates are sometimes of considerable thickness.

Dark-green plates of zinnwaldite, found in the stanniferous lodes in the granite and greisen of **Altenberg** (Saxony), have been long known as *Rabenglimmer*.

Much of the mica which accompanies cassiterite and tourmaline in the granite of **Cornwall** is doubtless to be referred to zinnwaldite, although some is lepidolite proper.

TOURMALINE

Tourmaline.—Borosilicate of aluminium and alkalies with iron and magnesium, containing also water (OH) and fluorine.

Hexagonal; symmetry, di-trigonal polar.

$$a = 113° 58', \quad [a : c = 1 : 0{\cdot}4476].$$

$a = \{1\bar{1}0\}$, $m = \{1\bar{2}1\}$, $m' = \{2\bar{1}\bar{1}\}$, R $= \{100\}$, $e = \{110\}$, $o = \{1\bar{1}1\}$, $x = \{2\bar{1}1\}$, $u = \{30\bar{2}\}$, $y = \{3\bar{1}\bar{1}\}$, C $= \{111\}$, R′ $= \{\bar{1}00\}$, $e' = \{\bar{1}\bar{1}0\}$, $o' = \{\bar{1}1\bar{1}\}$.

RR (100) : (010) $= 46° 52'$, CR (111) : (100) $= 27° 20'$, oo (1$\bar{1}$1) : (11$\bar{1}$) $= 77° 0'$, Co (111) : (1$\bar{1}$1) $= 45° 57'$, Rx (100) : (2$\bar{1}$1) $= 21° 41'$, uu (30$\bar{2}$) : (3$\bar{2}$0) $= 66° 1'$, ee (110) : (101) $= 25° 2'$.

Cleavage R, a, imperfect. Brittle. Fracture, sub-conchoidal. H $= 7$; G 3·1. Black (brown in thin splinters). Streak, colourless. Lustre, vitreous. Translucent; $\omega = 1{\cdot}64$. Birefringence, negative; $\epsilon - \omega = -0{\cdot}017$. Fusible. Insoluble in acids. Strongly pyro-electric and pleochroic.

With the above description compare crystals from **Mursinka** in the Urals.

Tourmaline, like mica, varies greatly in appearance and colour, on account of its wide variations in chemical composition. An analysis of the black tourmaline from Mursinka yielded $SiO_2 = 34{\cdot}88$, $B_2O_3 = 8{\cdot}94$, $Al_2O_3 = 34{\cdot}58$, $FeO = 14{\cdot}40$, $MgO = 1{\cdot}32$, $Na_2O = 2{\cdot}70$, $H_2O = 2{\cdot}87$, $F = 0{\cdot}51$, with small proportions of TiO_2, MnO, CaO, and K_2O. This and similar tourmalines correspond approximately to $H_6Na_2Fe_5Al_{14}B_6Si_{12}O_{63}$.

Tourmaline is of some importance as a rock-forming mineral; it is also especially interesting as one of the best and most conspicuous examples of polar symmetry (hemimorphism); the phenomenon of pyro-electricity was discovered in tourmaline, and its remarkable absorption has given it a special value as a material that can be used for producing plane-polarised light.

The name tourmaline appears to be of Cingalese origin; in the Middle Ages, and even at the present day among miners, ordinary black tourmaline was known by the name of "schorl," a word whose origin is doubtful.

Doubly terminated crystals are rare; they are found especially at localities where the mineral has crystallised out freely in limestone, or in gneiss or granulite. The microscopic crystals found in many sands may be recognised by their form (like Fig. 682); the more familiar museum specimens of tourmaline found in granite, etc., are generally attached by

an end; this is equally true of many minerals of polar symmetry. The symmetry is probably di-trigonal polar; it may possibly be really trigonal, and not di-trigonal, for several forms such as x and u have been sometimes observed to present only three faces at one end of a crystal; but the usual development of these faces in pairs and of $\{10\bar{1}\}$ as a hexagonal, and only of $\{1\bar{2}1\}$ as a trigonal prism, points to di-trigonal symmetry.

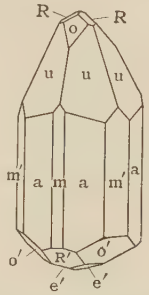


Fig. 682.—Tourmaline, R {100}, o {1$\bar{1}$1}, u {3$\bar{2}$0}, m {1$\bar{2}$1}, m' {2$\bar{1}\bar{1}$}, a {1$\bar{1}$0}, R′ {0$\bar{1}$0}, o' {$\bar{1}$11}, e' {$\bar{1}\bar{1}$0}, from Gouverneur, New York.

All coloured tourmalines possess a well-marked pleochroism; in black varieties ω green or blue, ϵ brown or red; it is less conspicuous in the yellow, brown, green, or red crystals, but in all of them the absorption of the ordinary ray is much greater than that of the extraordinary; this difference is so considerable in some of the dark-brown crystals that a section parallel to the optic axis transmits practically only the extraordinary rays (p. 138) and can be used as a polariser or analyser.

The interference-figure of a crystal section can be very well seen by placing it between two such plates, mounted in wire rings, kept together by a wire clip, and held close to the eye; this device is known by the name of the "tourmaline-tongs."

Sections of tourmaline suitable for this purpose are extremely rare,

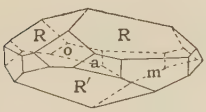


Fig. 683.—Tourmaline, R {100}, o {1$\bar{1}$1}, m' {2$\bar{1}\bar{1}$}, a {1$\bar{1}$0}.

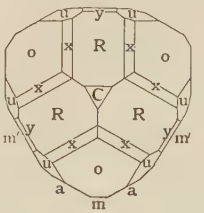


Fig. 684.—Tourmaline, antilogous end; from Pierrepont, New York.

but when good and only faintly coloured, they are to be preferred even to a nicol prism.

The pyro-electric property, which was first observed at the beginning of the eighteenth century, on the red crystals brought from Ceylon, can be very easily shown by means of Kundt's dusting method. It has commonly been supposed that the end which becomes negatively electrified during cooling (the analogous end) generally has the faces of the axial pyramid R over the faces of the trigonal prism m $\{1\bar{2}1\}$, and that at the antilogous end the faces of R are over the edges of the same prism, as in Fig. 190 (p. 77). Exceptions to this rule are, however, frequent, and are due to the presence of the supplementary prism m' $\{\bar{1}2\bar{1}\}$ instead of the more usual form m. Sometimes both prisms are present (Figs. 682, 684). The antilogous end is sometimes acute, owing to the development of u $\{03\bar{2}\}$ and other pyramidal forms which do not

occur at the other end; good examples of this habit are found among the brown crystals from Gouverneur, New York (Fig. 682). The antilogous end is also usually richer in faces than the analogous end. If the crystal be set with its antilogous end upwards, as in Figs. 682, 683, and 190, the indices of the forms will be as given on p. 538.

Characteristic features in the aspect of a tourmaline crystal, even when it has no terminations, are (1) the triangular cross-section, due to the predominance of the trigonal prism m or m', and (2) the vertical striations and consequent rounding of the prism-faces; these and the absence of cleavage serve to distinguish schorl from black hornblende and other minerals which it may resemble.

Juxtaposition-twins of tourmaline are almost unknown, but the alternation of analogous and antilogous patches on cross-sections points to supplementary twinning, similar to that of hemimorphite (p. 101).

The chemical composition of tourmaline has been, and still is, the subject of much discussion.

Rammelsberg suggested that all the tourmalines could be represented as derived from the acid H_6SiO_5, in which H_3 might be replaced by Al and B; H_2 by Fe, Mg, Mn, Ca; H by Na, K, Li.

Riggs proposed the formula $R_9 . BO_2 . (SiO_4)_2$, which was adopted by Jannasch and Kalb, and, in the form $R_6 . AlO . BO . (SiO_4)_2$, by Groth.

According to Clarke the composition may be represented by $H_{14}Al_5B_3Si_6O_{31}$, in which all the fourteen hydrogen atoms are replaceable by bases.

According to Penfield and Foote, the formula is $H_{11}Al_3B_2Si_4O_{21}$, in which two hydroxyl groups are associated with the boron, and the remaining nine hydrogen atoms are replaceable by bases: $H_9Al_3(BOH)_2Si_4O_{19}$.

A classification by composition and colour like that adopted above for the micas is scarcely possible in the case of tourmaline; but the alkali-tourmalines are generally red or green; the magnesia-tourmalines brown; the ferriferous tourmalines black. Transparent crystals are sometimes banded with zones of different colours, or are differently coloured at the two ends (*e.g.* those from Maine, U.S.A., and from Brazil).

Perfectly colourless tourmaline has been found and is distinguished as "achroite"; crystals of achroite from Elba are an alkali-tourmaline ($Na_2O = 2{\cdot}00$, $K_2O = 1{\cdot}30$, $Li_2O = 1{\cdot}22$ per cent) free from iron.

Tourmaline possesses a sufficiently high refractive index and hardness to make it an excellent gem stone; red varieties are known as "rubellite"; the indigo-blue variety as "indicolite." The mineral may be conveniently distinguished from other gem stones (except andalusite) by the use of a heavy liquid ($G = 3$ to $3{\cdot}2$) and of the total reflectometer ($\omega = 1{\cdot}64$), and by the pleochroism.

The best gem tourmalines are derived from the sand washings in Ceylon.

Tourmaline fuses (about 5 to 6) to a globule or a slag according to its composition; the boron, which it always contains, may be recognised by the green colour imparted to flame when the mineral, mixed with potassium bisulphate and fluor, is heated on a platinum wire. Some

varieties, especially the magnesia- and lithia-tourmalines only fuse with difficulty upon the edges.

Some Noteworthy Localities :

Elba.—In the granite of **San Piero** are veins which contain abundant tourmaline associated with white orthoclase, silvery mica, white and rose-coloured beryl, albite, quartz, and yellowish-red garnets. Some of the tourmaline is nearly black, especially at the edges of the veins ; but some of the druses contain beautiful rose-coloured crystals ; these are terminated by the basal plane C, which is dull at the analogous and bright at the antilogous end ; the crystals are never doubly terminated and generally present the analogous end.

This granite also yields green crystals, and the colourless achroite, and also prisms showing alternating bands of red and green.

Campolongo (Switzerland).—The white granular dolomite, already mentioned as the matrix of corundum, yields also green prisms of tourmaline with alternate edges truncated by small faces of *m*, terminated by *o*, the edges of which are truncated by small faces of R. Silvery mica, diaspore, calcite, red and blue corundum are the associated minerals.

Ural Mountains.—At **Schaitanka** near Ekaterinburg, in a coarse granite, associated with albite, smoky quartz, green mica, and pink lepidolite, are found in the druses beautiful red crystals of rubellite, striated prisms *a*, terminated by C at the analogous, and by R at the antilogous end. At **Mursinka,** about thirty miles north, in the albitic granite which produces topaz and beryl, is found fine black tourmaline noteworthy as often doubly terminated ; R is bright at the analogous, and dull at the antilogous end.

New York.—At **Gouverneur** in St. Lawrence County are found large brown crystals associated with apatite and scapolite in a granular limestone. In these the polar character is very well marked by the acute termination of the antilogous pole (Fig. 682).

At **Pierrepont** the limestone contains fine black tourmaline associated with dark phlogopite, pyroxene and rounded quartz.

Devonshire and Cornwall.—At **Chudleigh** near Bovey Tracey in Devonshire a granite quarry formerly yielded large crystals of black tourmaline associated with large grey opaque prisms of apatite. The tourmaline is in short, thick columns, of twelve-sided cross-section, owing to the presence of the hexagonal prism *a* and both the trigonal prisms, *m* and *m'*, of which *a* is bright and *m m'* are dull, while *m'* is usually larger than *m*. The analogous end is remarkably rough and rounded, with scarcely recognisable faces, while the antilogous end shows bright faces of R and *o*.

In many localities in Cornwall the granite contains black tourmaline ; the common schorl, especially in the decomposed granite of **St. Austell** which yields china-clay, is in fine needles, which often assume the form of a fibrous or silky mass.

THE SCAPOLITE GROUP

In connection with the foregoing fluoriferous silicates, mention may here be made of a group of minerals some of whose members contain chlorine as an essential constituent.

Scapolite (or wernerite) is a tetragonal mineral, found in large opaque white crystals with augite and hornblende in limestone at Arendal in Norway. Here and at other localities the mineral is usually somewhat altered, but may be recognised by its tetragonal form (Fig. 685) ($r = \{111\}$, $h = \{210\}$) and two sets of rectangular cleavages A, m. A similar mineral is found in the metamorphic rocks, especially the limestone and magnetite of Finland, Sweden, and the United States, and when massive resembles felspar in appearance. In composition it is an alumo-silicate of calcium containing also alkalies, water, and some chlorine. As the proportion of silica increases the proportion of alkalies and chlorine increases also.

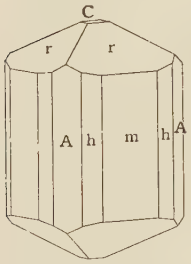


Fig. 685. — Scapolite, A {100}, m {110}, h {210}, r {111}, C {001}.

In the ejected limestone blocks of Monte Somma (Vesuvius) are found small limpid glassy tetragonal prisms having the same angles and cleavage; these are known as **meionite** and have the composition $Ca_4Al_6Si_6O_{25}$ ($SiO_2 = 40{\cdot}5$). In the trachyte of Monte Somma are found similar crystals containing about 55 per cent of silica, which are distinguished as **mizzonite.** Finally, in the volcanic piperno of Pianura near Naples occur crystals belonging to the same group, and approximating to the composition $Na_4Al_3Si_9O_{24}Cl$, which requires $SiO_2 = 64{\cdot}0$, $Cl = 4{\cdot}2$. These are known as **marialite.**

It has been suggested by Tschermak that all the minerals of the scapolite group may be represented as mixtures, in varying proportions, of meionite (Me) and marialite (Ma); the common scapolite approximates to Me_3Ma.

The scapolites show a close chemical relationship to the felspars; and a similarity in composition is apparent if their formulæ be written:

$(NaAlSi_3O_8)_3 . NaCl$ . . . Ma
$(CaAl_2Si_2O_8)_3 . CaO$ . . . Me

corresponding to albite and anorthite respectively.

The pseudo-tetragonal character of the felspars (p. 516) may be recalled in this connection.

Some members of the group have been found to contain small proportions of CO_2 or SO_3; and in these it appears that Na_2CO_3 or Na_2SO_4 (or $CaCO_3$ or $CaSO_4$) takes the place of NaCl or CaO in the above formulæ.

According to Groth these constituents may probably play the same part as in the sodalite group (p. 509), so that the constitution of marialite will be $Na_4Al_2(AlCl)''(Si_3O_8)_3$, and that of a meionite containing CO_2 will be $Ca_4Al_5(AlCO_3)'(Si_2O_8)_3$.

SECTION XXII

THE ZEOLITES

Under the name zeolites are classed together a number of hydrated silicates of alumina and alkalies, most of which also contain lime; their water is very loosely held, and they intumesce before the blowpipe; the name zeolite (ζέω, I boil) was given in allusion to this property. They are mostly fusible and decomposed by acids, and have a vitreous or pearly lustre and a specific gravity about 2·3.

They are found, often beautifully crystallised, as decomposition products lining cavities in altered igneous rocks, having mainly been derived from the felspar; in fact some of the zeolites have practically the composition of hydrated felspar; thus, stilbite corresponds to two molecules of albite, with Ca in place of Na_2 and with 6 molecules of water; thomsonite corresponds to anorthite with $2\frac{1}{2}$ molecules of water.

THE STILBITE GROUP

Stilbite.—Hydrated silicate of calcium and aluminium; $CaAl_2Si_6O_{16}.[6H_2O]$;[1] $CaO = 9·0$, $Al_2O_3 = 16·3$, $SiO_2 = 57·5$, $H_2O = 17·2$. Some Ca is almost always replaced by Na_2.

Monoclinic.

$$a : b : c = 0·7623 : 1 : 1·1940. \quad \beta = 50° 50'.$$

$$C = \{001\},\ B = \{010\},\ m = \{110\}.$$

$$mm\ (110) : (1\bar{1}0) = 61° 10',\ Cm\ (001) : (110) = 57° 4'.$$

Twinned on C. Cleavage B, perfect. Brittle. Fracture, uneven. H = $3\frac{1}{2}$; G = 2·2. White. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1·498$. Birefringence weak, negative; $\gamma - \alpha = 0·006$. Axial plane B. Acute bisectrix inclined at 85° to the normal of C, and at 34° 10′ to the normal of A (100). $2E = 51\frac{1}{2}°$; $\rho < v$. Fusible ($2\frac{1}{2}$). Decomposed by hydrochloric acid.

With the above description compare crystals from **Talisker** in Skye.

Stilbite is found in beautiful crystals in the amygdales of trap-rocks in several parts of the world; they resemble a combination of an orthorhombic pyramid with {100} and {010}, but are in reality interpenetrant

[1] The brackets [ ] in the formulæ of the zeolites indicate that the amount of water is variable. (See p. 232.)

twins, a combination of CB*m*, united by twinning on C, as shown in Fig. 686.

The pearly lustre and perfect cleavage of the face B is very characteristic, and the crystals are usually plates flattened parallel to this face. There is also an imperfect cleavage parallel to C. The extinction-angle on a cleavage-flake B with regard to the basal plane C is 5°, and the flake is perpendicular to the third mean line; the twinning is generally recognisable in a cleavage-

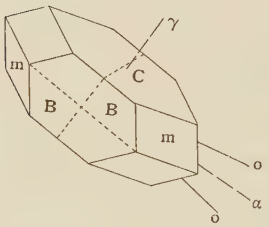


Fig. 686.—Stilbite, B {010}, *m* {110}, C {001}, twinned on (001).

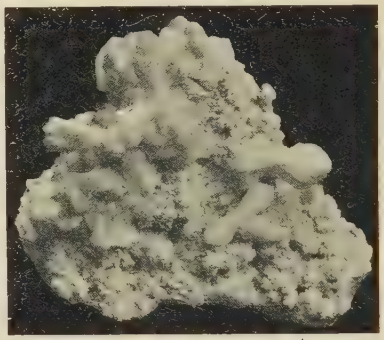


Fig. 687.—Stilbite from Berufjord, Iceland (British Museum).

flake by division into sectors whose extinction-directions are inclined at 10° to each other.

Crystals having the form of Fig. 686 are often aggregated into bundles or sheaves, as shown in Fig. 687.

At some localities the mineral is of a brick-red colour.

Before the blowpipe, stilbite fuses to a white enamel after intumescence; it is decomposed by hydrochloric acid, without gelatinisation, but with separation of slimy silica.

Some Noteworthy Localities:

Poonah (India).—Large salmon-coloured crystals of tabular habit are found in amygdales of the trap of this district associated with large colourless crystals of apophyllite, and striated prisms of scolecite; the smaller amygdales are sometimes filled or lined with a green earthy mineral which appears to be an impure stilbite.

Scotland.—Amygdales in the basalt of **Talisker** in Skye contain crystals of the habit of Fig. 686 situated upon a finely fibrous mealy zeolite (mesolite). At **Campsie** in Stirlingshire and **Kilpatrick** in Dumbartonshire amygdales of the decomposed basalt are lined with fine red crystals of stilbite associated with heulandite of the same colour.

Faroe Islands. The basalt contains cavities lined with fine white crystals of tabular stilbite accompanied by apophyllite and a fibrous or spheroidal thomsonite known as "faroelite."

Fig. 687, from a photograph of a specimen from Berufjord in Iceland, illustrates the manner in which stilbite often occurs aggregated into sheaves

which spread out at the two ends. Stilbite has already been mentioned as encrusting the Iceland spar of Eskifjördhr (p. 456).

Phillipsite may perhaps be $CaAl_2Si_5O_{14} . [5H_2O]$, in which variable proportions of Ca are replaced by equivalent proportions of K and Na; it has nearly the same form as stilbite: $mm = 60° 42'$, $Cm = 60° 50'$. The crystals present a singular cruciform appearance, Fig. 688, and simulate tetragonal symmetry. That they are not single crystals is easily seen from their stellate shape and the slightly re-entrant angles at their ends, and from the striæ. Such a crystal is due to the interpenetration of two twinned crystals similar to Fig. 686 of stilbite. Each arm of the cross consists of two individuals twinned thus on C, and the two arms are united by twinning on (011). The angle (001) : (011) = 46° 2′, so that the two arms are nearly at right angles to each other, and if the grooves along the edges

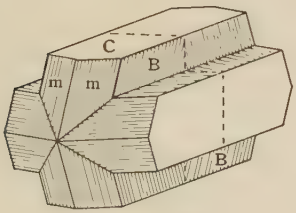


Fig. 688.—Phillipsite.

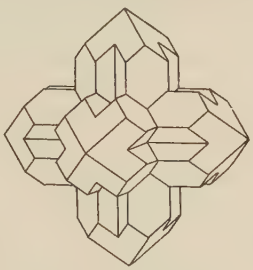


Fig. 689.—Phillipsite.

are small the whole group may present the appearance of a tetragonal prism and pyramid. Occasionally three (or six) such groups are found twinned together on faces of m {110} to form a still more complex group (Fig. 689), which resembles the rhombic dodecahedron of the cubic system, since (110) : $(1\bar{1}0) = 60° 42'$ and (110) : (011) = 45° 55′, so that the a-axes of the three groups are nearly at right angles (88° 10′). Phillipsite thus affords a striking instance of a complex pseudo-symmetric crystal formed by the mimetic twinning of pseudo-cubic individuals. The crystals cleave parallel to B (also C), but not nearly so distinctly as stilbite and heulandite; B is perpendicular to an obtuse negative bisectrix. Phillipsite generally occurs in colourless glassy crystals lining cavities in basalt with other zeolites. Before the blowpipe it fuses to a white enamel, but without the lively intumescence of stilbite.

Harmotome may have the composition $BaAl_2Si_5O_{14} . [5H_2O]$ corresponding to phillipsite. In crystalline form, habit, and twinning it very closely resembles that mineral, and is also found in the cavities of basalt. It is somewhat denser (G = 2·5) than phillipsite (G = 2·2), and is fusible with greater difficulty, and without exfoliation.

Among typical localities of harmotome may be mentioned Andreasberg in the Harz, where it occurs in white crystals with calcite, quartz, galena, etc., as a constituent of the metalliferous veins which traverse the slate

(Fig. 690). At Strontian in Argyllshire fine translucent crystals occur with calcite and barytes in veins of the granite.

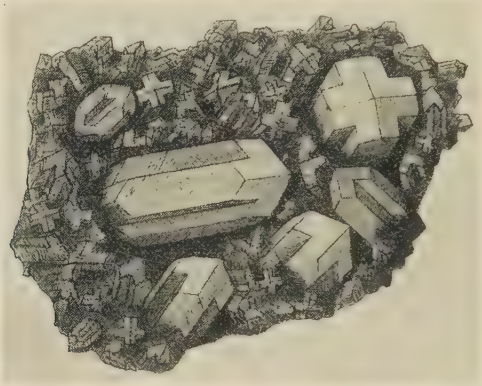


Fig. 690.—Harmotome from Andreasberg.

Some specimens of stilbite and phillipsite contain less silica than would correspond with the above formulæ, and it has been suggested that the minerals of this group may in fact be isomorphous mixtures of two compounds $CaAl_2Si_6O_{16} \cdot [5H_2O]$ and $CaAl_2Si_2O_8 \cdot [3H_2O]$, corresponding to a hydrated lime-albite and a hydrated anorthite (of which the former has the composition given above for stilbite), respectively, and the corresponding sodium and barium compounds (*cf.* p. 554).

These minerals also show a remarkable similarity to the felspars in their angles and modes of twinning. Thus the simple twins of stilbite (Fig. 686) correspond to the Manebach twins of orthoclase, and the complex twins of harmotome and phillipsite resemble the multiple groupings on the Baveno law.

THE HEULANDITE GROUP

Heulandite.—Hydrated silicate of calcium and aluminium ; $CaAl_2Si_6O_{16} \cdot [5H_2O]$; CaO = 9·2, Al_2O_3 = 16·8, SiO_2 = 59·2, H_2O = 14·8. Some Ca is usually replaced by Na_2.

Monoclinic.

$$a : b : c = 0{\cdot}4035 : 1 : 0{\cdot}4293. \quad \beta = 88° 34'.$$

$$B = \{010\},\ C = \{001\},\ t = \{201\},\ s = \{20\bar{1}\},\ m = \{110\}.$$

$mm\ (110) : (1\bar{1}0)$ 43° 56′, $Ct\ (001) : (201)$ = 63° 40′, $Cs\ (001) : (\bar{2}01)$ = 66° 0′.

Cleavage B, perfect. Brittle. Fracture, uneven. H = 3½ to 4 ; G = 2·2. White. Streak, colourless. Lustre, vitreous (pearly on B). Translucent. $\beta = 1{\cdot}499$. Birefringence, weak, positive ; $\gamma - \alpha = 0{\cdot}007$. Axial plane and acute bisectrix perpendicular to B. Obtuse bisectrix inclined at 82° to the normal of C (001) and at 6½° to the normal of A (100). 2E = 50° (variable). Fusible. Decomposed by hydrochloric acid.

With the above description compare crystals from **Berufjord** (Iceland).

Heulandite has nearly the same composition as stilbite, differing only in the proportion of water; it occurs under the same conditions, often together with stilbite, and much resembles it in appearance, but has a different crystalline form; the crystals, like those of stilbite, are sometimes colourless or white, but sometimes red, and possess a similar perfect cleavage; they have a characteristic coffin-shaped habit, as shown in Fig. 691. The perfect cleavage is parallel to B {010} and has a pearly lustre even more pronounced than that of stilbite.

As is seen from Fig. 691, the cleavage B is perpendicular to the acute positive bisectrix (2E = 50° about), and this affords a ready means of

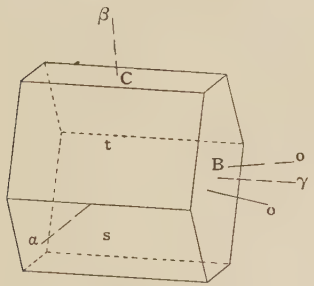


Fig. 691.—Heulandite, B {010}, C {001}, *t* {201}, *s* {20$\bar{1}$}.

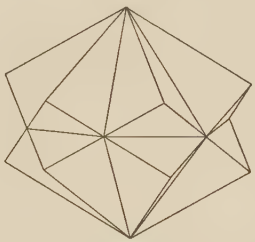


Fig. 692.—Chabazite, {100}, twinned on the axis [111].

distinguishing heulandite from stilbite; in most respects the two minerals are closely alike.

The name stilbite was given from the word $\sigma\tau\acute{\iota}\lambda\beta\omega$, I shine, and heulandite is named after a well-known mineral collector; in German textbooks and treatises the mineral here called stilbite is named desmine, and our heulandite is sometimes called stilbite.

At Strontian, the original locality for strontianite, are found also grey pearly crystals of **brewsterite**, a mineral having the formula of heulandite in which Ca is partially replaced by Ba and Sr; it is isomorphous with heulandite.

THE CHABAZITE GROUP

Chabazite, $CaAl_2Si_4O_{12} . [6H_2O]$, in which varying proportions of Ca are replaced by Na_2 and K_2, crystallises in rhombohedra of 85° 14′, and occurs in glassy white or pink crystals. The rhombohedron is almost always striated parallel to its edges, and the crystals are usually interpenetration-twins united by hemitropy about the principal axis, as shown in Fig. 692. This is so characteristic that chabazite may generally be recognised by the twinning, which makes the crystals somewhat resemble fluor; the striations, and a fair cleavage parallel to the rhombohedron, distinguish it from that mineral.

Beautiful white crystals of chabazite have been found in cavities of the basalt of the Giant's Causeway.

Flat rhombohedra, with {110} predominant, showing the same interpenetration-twinning, have been found at several localities and have received the name "phacolite"; these are often lenticular (*φακός*, a lentil). Beautiful glassy crystals of this variety have been found in cavities of a compact basalt at Richmond in Victoria, and are associated with phillipsite, analcite, calcite, sheaf-like stilbite, and radiating bundles of a brown ferriferous calcite. This variety is sometimes known as "seebachite."

Gmelinite is the name given to the corresponding sodium compound, $Na_2Al_2Si_4O_{12} . [6H_2O]$, isomorphous with chabazite and twinned in the same manner. Owing to the development of the inverse rhombohedron {$\bar{1}22$}, together with R {100} (*cf.* Fig. 162, p. 68), the crystals resemble hexagonal bipyramids, but the twinning may be detected by the re-entrant angles upon their edges.

Fine pink rhombohedra of this mineral occur, with pink phillipsite, natrolite and analcite, in cavities of the basalt of Magee Island (Antrim).

The proportion of silica in chabazite and gmelinite varies in different occurrences; and, as in the case of the stilbite group, these minerals may possibly be mixtures of hydrated felspathic compounds: $CaAl_2Si_6O_{16} . [8H_2O]$ and $CaAl_2Si_2O_8 . [4H_2O]$ (and corresponding sodium compounds). The formula for chabazite given above would correspond to a mixture of these in the proportion 1 : 1.

ANALCITE

Analcite.—Hydrated silicate of sodium and aluminium; $NaAlSi_2O_6 . [H_2O]$; $Na_2O = 14{\cdot}1$, $Al_2O_3 = 23{\cdot}1$, $SiO_2 = 54{\cdot}6$, $H_2O = 8{\cdot}2$. Cubic; common form, {211}, with {100}. Brittle. Fracture, uneven. H = 5½; G = 2·2. Colourless. Streak, white. Lustre, vitreous. Transparent; $\mu = 1{\cdot}487$. Fusible (2½). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from the **Cyclopean Islands.**

Analcite is found at several localities in clear glassy icositetrahedra {211}, like Fig. 33, p. 20, either alone or in combination with the cube (Fig. 693), but the crystals are often opaque and white or pink in colour, *e.g.* the large white crystals found with quartz, calcite, platy apophyllite and natrolite in amygdaloidal cavities in melaphyre at the Seisser Alp in the Tyrol. Analcite has the composition of a hydrated leucite, with sodium taking the place of potassium. It also resembles leucite in form, just as stilbite and phillipsite resemble felspar. Analcite almost always exhibits weak birefringence, and is resolved under the microscope into sectors which do not extintinguish together. The crystals may therefore perhaps (like leucite) be pseudo-cubic. These "optical anomalies" will be considered below, with the optical characters of the zeolites as a whole.

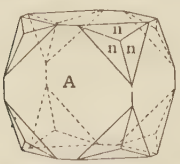


Fig. 693.—Analcite from Cyclopean Islands, A {100}, *n* {211}.

Before the blowpipe analcite fuses to a colourless glass, and the large

percentage of sodium is indicated by the yellow colour imparted to the flame.

The name was given in allusion to its weak electrification by friction (ἀναλκις, weak).

A Noteworthy Locality :

Cyclopean Islands (near Sicily).—Beautiful glassy crystals occur in the cavities of doleritic rock ; these cavities are generally lined or filled with analcite, which is sometimes so large that one crystal may entirely fill a cavity. The crystals are a combination of {100} and {211} (Fig. 693), and possess a lustre like that of limpid quartz. The cube-faces are usually replaced by vicinal planes of a flat icositetrahedron.

THE NATROLITE GROUP

Natrolite.—Hydrated silicate of sodium and aluminium ; $Na_2Al_2Si_3O_{10} . [2H_2O]$; $Na_2O = 16{\cdot}3$, $Al_2O_3 = 26{\cdot}8$, $SiO_2 = 47{\cdot}4$, $H_2O = 9{\cdot}5$.

Orthorhombic.

$$a : b : c = 0{\cdot}978 : 1 : 0{\cdot}354$$

$$m = \{110\},\ o = \{111\}.$$

$$mm\ (110) : (1\bar{1}0) = 88° 45',\ mo\ (110) : (111) = 63° 11',\ oo = (111) : (\bar{1}11) = 37° 38',$$
$$oo = (111) : (1\bar{1}1) = 36° 47'.$$

Common form, *mo*. Cleavage *m*, perfect. Brittle. Fracture, uneven. $H = 5\frac{1}{2}$; $G = 2{\cdot}2$. Colourless. Streak, white. Lustre, vitreous. Transparent ; $\beta = 1{\cdot}479$. Birefringence, positive, weak ; $\gamma - \alpha = 0{\cdot}012$. Axial plane (010). Acute bisectrix normal to (001). $2E = 99°$; $\rho < v$. Readily fusible (2). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from **Puy de Dôme.**

Natrolite is the commonest of the fibrous zeolites ; it sometimes occurs in the amygdaloidal cavities of basalt in beautiful tufts of acicular crystals, and it is common as a massive radial-fibrous mineral.

When terminated, the crystals always present the appearance of square prisms terminated by square pyramids (Fig. 694), sometimes with {010} (*cf.* Fig. 695, scolecite). The angles given above indicate that the symmetry is very nearly tetragonal.

Under the microscope natrolite may be recognised by the straight extinction and absence of visible bisectrix or optic axes in a cleavage-flake.

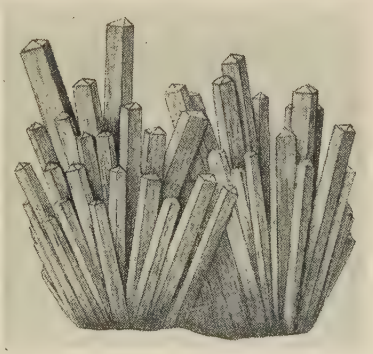


Fig. 694.—Natrolite from Puy de Dôme.

It is so fusible that it can be melted in a candle flame, and the colour which it imparts to flame indicates a compound rich in sodium.

A Noteworthy Locality:

Puy de Marman (Puy de Dôme, France).—Beautiful white crystals were formerly found here in the cavities of a compact basalt associated with calcite, aragonite, and analcite; these are much larger than the natrolite crystals of most localities. Here, as elsewhere, the prisms are never doubly terminated.

Scolecite.—Among the other acicular or fibrous zeolites the most important is scolecite, a lime zeolite, $CaAl_2Si_3O_{10} \cdot [3H_2O]$, corresponding to natrolite in composition, except for the difference of water. It occurs in crystals having almost exactly the angles of natrolite, and similar cleavage, but when examined carefully the crystals will be seen to present signs of twinning. They consist, in fact, of two monoclinic crystals, a combination of *m* {110}, B {010}, *o* {111}, *d* {101}, united by twinning and juxtaposition along the plane (100) (Fig. 695). Re-entrant angles can generally be seen where the faces of {111} of one individual nearly, but not quite, coincide with the faces of {$\bar{1}$11} of the other. Further, the extinction on the face B is not straight, as in natrolite, but is inclined at 15° to the vertical; in such a twin, therefore, the two halves of the plane B extinguish in positions inclined at 30° to each other. The birefringence of scolecite is negative, and B is perpendicular to a positive obtuse bisectrix, whereas in natrolite B is perpendicular to the third mean line. The axial plane and acute bisectrix are inclined at 15° to the vertical.

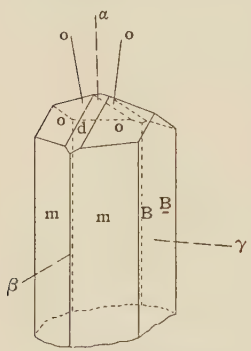


Fig. 695.—Scolecite, B {010}, *m* {110}, *o* {111}, *d* {101}, twinned on (100).

Etching experiments on scolecite and also its pyro-electricity show that this mineral is not holosymmetric but possesses only a plane (without an axis) of symmetry (*cf.* pyroxene, p. 478); the back and front prism-faces are electrically opposite in character; in the twins they are alike.

Scolecite is named from σκώληξ, a worm, in allusion to the manner in which it curls up when fused before the blowpipe (fusibility slightly above 2). With acids it behaves like natrolite.

The best crystals of scolecite are the large striated prisms which accompany the pink stilbite on the beautiful specimens from Poonah which have been described on p. 544. It also occurs in fibrous aggregates.

Another mineral belonging to this group is **mesolite,** which, as indicated by its name, is intermediate in composition between natrolite and scolecite and appears to be a mixture of the two.

It usually occurs in downy white masses of minutely acicular crystals, or occasionally (crystals from Poonah) as radiating prisms resembling natrolite, though without end faces.

In mesolite, however, the optic axial plane is transverse to the prism, and one optic axis is visible through each face of the prism, whose angle is

88° 31′. The double refraction is very weak ($\gamma - \alpha = 0{\cdot}0004$), and owing to strong dispersion of the optic axes the prism-faces show characteristic dark blue and yellow colours between crossed nicols. The extinction on transverse sections indicates that the crystals belong to the anorthic system.

Another fibrous or prismatic zeolite which may occur with those already mentioned is the orthorhombic **thomsonite,** also a soda-lime zeolite. This may be recognised under the microscope by the principal cleavage, (010), being perpendicular to the positive acute bisectrix ($2E = 90°$), and giving straight extinction with regard to the second cleavage (100). The axial plane is at right angles to the cleavages.

THE WATER AND OPTICAL PROPERTIES OF THE ZEOLITES

As has already been mentioned (p. 232), the water of the zeolites behaves on heating in quite a different way from the water of crystallisation of most minerals and hydrated salts, inasmuch as its amount diminishes in a regular and continuous manner as the temperature is raised, instead of being given off at one or more definite temperatures, and it may be re-absorbed on cooling and exposure to damp air. Heulandite from the Faroe Islands lost 12·3 per cent of water on being heated to 190° C., and in ordinary air regained 10·1 per cent in two months.

Most zeolites give off some of their water on exposure to dry air even at the ordinary temperature, and regain it in a moist atmosphere. Thus, chabazite from Bohemia lost 7·2 per cent in dry air in seven months, and regained it in twenty-four hours on being left exposed to the air.

It has been shown by G. Friedel that the water in a zeolite exerts a definite vapour-pressure, which increases with rise of temperature, and at a given temperature varies continuously with the percentage of water in the mineral, and that an equilibrium is set up when this pressure is equal to the tension of aqueous vapour in the surrounding atmosphere, water being given off, or absorbed, until this condition is attained.

Thus, for example, chabazite from Bohemia, in contact with air which had been saturated with water vapour at 6·5° (vapour-tension = 7·3 mm.) was found to contain: at 12°, 22·5 per cent; at 148°, 12 per cent; at 263°, 3½ per cent; and at 410°, 1½ per cent of water. The water lost was reabsorbed on cooling provided that the maximum temperature had not been above a red heat. Analcite behaves in a similar way, except that the loss and reabsorption of water do not take place below about 100°.

The water of crystallisation of ordinary hydrated salts, on the other hand, commonly has a vapour-pressure below that of the moisture in the surrounding air, and does not begin to escape until on heating its vapour-pressure attains this value, when it goes off without further rise of temperature until the whole of the salt is converted into the anhydrous state, or into a lower hydrate, each hydrate containing a definite molecular proportion of water.

Since the amount of water in a given zeolite varies with the temperature and pressure, it is obvious that the formula of the mineral will not necessarily show a whole number of molecules of water; and the weight of a given crystal will vary with the humidity of the air.

It is possible that in some zeolites some portion of the water may be combined to form part of the chemical molecule, though this is uncertain. Thus a lime silicate known as laumontite, $CaAl_2Si_4O_{12} . [4H_2O]$, which contains in all about 15·3 per cent of water, and in dry air at the ordinary temperature loses 3 to 4 per cent and crumbles to pieces, loses 7·28 per cent (or about one-half) on heating to 300°, while the remainder only goes off at a red heat. Hence the formula is sometimes written $H_4CaAl_2Si_4O_{14} . 2H_2O$.

Similarly in heulandite, a portion of the water requires a red heat for its expulsion, and the formula is usually regarded as $H_4CaAl_2Si_6O_{18} . 3H_2O$. Rinne found, however, that the loss of water was gradual at increasing temperatures, up to 555° C. (a low red heat = 525°), so there seems to be no good ground for separating the water into two portions in this way.

With loss of water the zeolites gradually lose their transparency and become dull, but on reabsorption of it they again become transparent and regain their original optical properties; this seems to indicate that the crystal edifice is not destroyed when the water is removed, and that the water can re-enter the meshes of the structure.

A still more remarkable feature of the zeolites is that after their water has been driven off by heat its place may be filled by various other substances, such as air, ammonia, hydrogen, carbon dioxide, alcohol, and even iodine or mercury, simply by allowing the dehydrated mineral to cool in contact with the gas or vapour.

Thus, dehydrated chabazite cooled in dry air can absorb 2·7 per cent of its original weight, or fifty times its volume, of air; cooled in dry ammonia it may absorb 14 per cent. The same mineral heated with mercury to 300° absorbed 27 per cent of its own weight of mercury.

The absorption takes place with considerable avidity and is accompanied by evolution of heat.

In most zeolites the loss of water produces well-defined optical changes. Thus in heulandite Mallard showed that if the mineral be heated up to 150° the extinction-angle on B and the angle between the optic axes gradually change as the water is gradually lost, and return to their original values as it is reabsorbed.

The behaviour of heulandite on heating has been examined in detail by Rinne. At the ordinary temperature the axial plane is nearly parallel to C (001), the acute bisectrix (γ) being perpendicular to (010) (Fig. 691). During heating the optic axes close in upon the normal of B, and at about 80° coincide ($\beta = a$). They then open out in a plane almost at right angles to the original axial plane, until at 180° they coincide again, in a line (a) nearly perpendicular to C (001), when $\beta = \gamma$. At 180° the crystal becomes opaque and no longer reabsorbs water so readily on cooling. Rinne found, however, that by immersing in oil heulandite which has been thus altered, it becomes transparent and still possesses the

definite optical characters of a crystal; the crystalline structure has therefore not been destroyed. The oil enables the effect of heating to be followed further. Thus above 180° the optic axes are seen to open out again, this time in the plane of symmetry, until at 280° they again coincide in a line (γ) nearly perpendicular to s ($20\bar{1}$). Above 280° they once more open out at right angles to the symmetry-plane.

Many zeolites thus transformed by heat may be soaked in oil, which prevents reabsorption of water, and makes the optical properties of the dehydrated crystal visible and permanent. For example, natrolite heated to 250° loses most of its water and becomes dull; but, immersed in oil, it is found to possess the optical characters of a monoclinic crystal with its axis of symmetry parallel to the edges of the prism.

Further changes in the optical properties are produced by the replacement of the water by other substances. Thus a crystal of chabazite, colourless and optically negative in the natural state, becomes positive when dehydrated and saturated with ammonia, and brown and strongly pleochroic by absorption of iodine.

From these and similar observations it is to be concluded that the water of the zeolites is not analogous to the water of crystallisation of most hydrated salts, but is held in the meshes of the structure formed by the lattice of the silicate, after the manner of that in a sponge, or perhaps in a state of condensation or "adsorption" on the framework of the structure, as it frequently is on the external surface of bodies or in porous substances like opal.

Among the zeolites not only is twinning very prevalent, as has been shown above, but even apparently simple crystals, or the portions which unite to form an interpenetrant twin, are usually found to be pseudo-symmetric when their optical properties are examined. Sections of heulandite, phillipsite, harmotome, stilbite, chabazite, gmelinite, analcite, all show differently orientated sectors or patches which do not extinguish together when the section is examined between crossed nicols.

Analcite, though cubic in form, almost always shows a weak double refraction. The birefringence increases on heating but does not undergo an abrupt change at a certain temperature, like that of leucite, which suddenly becomes isotropic near 700° owing to a polymorphous change. The birefringence has been attributed by some authors to internal strain, caused possibly by a slight loss of water, since crystals are stated by Klein to become isotropic on heating in a moist atmosphere. Others, however, with Mallard, consider the crystals to be pseudo-symmetric twins of (perhaps) tetragonal material. In the case of chabazite the rhombohedral crystal is sometimes uniaxial, sometimes slightly biaxial, and the birefringence is sometimes positive and sometimes negative. This behaviour, as explained on p. 261, points to an isomorphous intermixture of two substances of different optical characters. Now chabazite varies considerably in composition, particularly in the proportions of silica and of water; accordingly many attempts have been made to explain its constitution as a mixture of two isomorphous compounds. Streng suggested $CaAl_2Si_2O_8 . 4H_2O$ and $CaAl_2Si_6O_{16} . 8H_2O$, two compounds which display

a relationship in composition somewhat similar to that of the felspars and correspond (apart from water) to anorthite and to a lime-albite, respectively.

Similarly in the phillipsite group : phillipsite is represented by Groth (following W. Fresenius) as a mixture of two compounds $CaAl_2Si_2O_8 . 3H_2O$ and $CaAl_2Si_6O_{16} . 6H_2O$, and other authors have proposed other formulæ.

On the other hand, it has been suggested by Friedel that the variable proportion of silica may be due to the presence of free silica contained in the meshes of the structure in the same kind of way as is the water. Such an internal precipitation of silica has been produced artificially in chabazite.

SECTION XXIII

SILICATES CONTAINING WATER OF CONSTITUTION

THE EPIDOTE GROUP

Epidote.—$HCa_2Al_3Si_3O_{13}$; $CaO = 24{\cdot}7$, $Al_2O_3 = 33{\cdot}7$, $SiO_2 = 39{\cdot}6$, $H_2O = 2{\cdot}0$; but containing Fe_2O_3 (up to 16 per cent), replacing Al_2O_3.

Monoclinic.

$$a : b : c = 1{\cdot}579 : 1 : 1{\cdot}804. \quad \beta = 64° 37'.$$

A = {100}, C = {001}, e = {101}, i = {$\bar{1}$02}, r = {$\bar{1}$01}, l = {$\bar{2}$01}, f = {$\bar{3}$01}, n = {$\bar{1}$11}, o = {011}, k = {012}, d = {111}, z = {110}, u = {210}, q = {22$\bar{1}$}, y = {21$\bar{1}$}, B = {010}.

AC (100) : (001) = 64° 37′, Ci (001) : ($\bar{1}$02) = 34° 21′, ir ($\bar{1}$02) : ($\bar{1}$01) = 29° 21′, Bo (010) : (011) = 31° 32′, Bn (010) : ($\bar{1}$11) = 35° 14′, An (100) : (11$\bar{1}$) = 69° 2′, on = (011) : ($\bar{1}$11) = 33° 56′, on = (011) : (11$\bar{1}$) = 55° 46′.

Twinned on A. Cleavage C, perfect; A, imperfect. Brittle. Fracture, uneven. H = 6½; G = 3·4. Dark green. Streak, grey. Lustre, vitreous. Translucent; $\beta = 1{\cdot}754$, $a = 1{\cdot}731$ (red). Birefringence, strong, negative; $\gamma - a = 0{\cdot}037$. Axial plane, B. Acute bisectrix inclined at 22° 37′ to normal of C, and at 87° 14′ to normal of A; 2V = 73° 48′ (red). Dispersion (inclined), strong, $\rho > v$. Pleochroism, strong. Fusible with difficulty (3½). Partially decomposed by hydrochloric acid.

With the above description compare crystals from **Untersulzbachthal** (Salzburg).

Epidote is a not uncommon rock-constituent; the best specimens are found in druses of the crystalline schists, generally in long prisms, and, unlike most monoclinic minerals, elongated along the axis of symmetry. The crystals are sometimes very rich in faces, both in the principal striated zone of the orthodomes [*eir*], and also in the pyramidal termination *o*, *n*, etc. (Fig. 697). They are excellent material for practice in goniometrical measurement and calculation. Twinning is very frequent, and may generally be recognised by a re-entrant angle dividing the terminal faces by a nick, or a twin-lamella parallel to A (Fig. 698). The crystals are also sometimes twinned parallel to C.

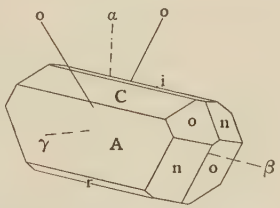


Fig. 696. — Epidote, A {100}, C {001}, i {$\bar{1}$02}, r {10$\bar{1}$}, o {011}, n {$\bar{1}$11}.

Ordinary massive epidote is a compact or granular yellowish-green

substance which may be confused with massive pyroxene or idocrase; but the (pistachio green) colour is really somewhat different from that of other minerals. Thin crystals may be pale green; ordinary crystals are often nearly black.

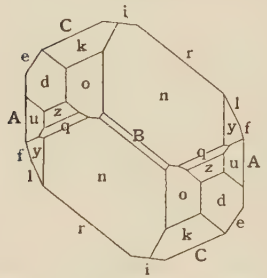


Fig. 697[1].—Epidote, A {100}, *e* {101}, C {001}, *i* {$\bar{1}$02}, *r* {$\bar{1}$01}, *l* {$\bar{2}$01}, *f* {$\bar{3}$01}, *k* {012}, *d* {111}, *o* {011}, *n* {$\bar{1}$11}, *z* {110}, *q* {22$\bar{1}$}, *u* {210}, *y* {21$\bar{1}$}.

Under the microscope epidote usually shows strong pleochroism (β brown, α and γ yellow to green), and the optic axes are visible in succession (through C and *r*) as a prism is turned round; the obtuse bisectrix is nearly perpendicular to A. The interference-figure is generally complicated by the twinning.

Certain crystals of dark green epidote which are transparent possess a very remarkable property, due to the strong absorption; when looked through in the direction of an optic axis they exhibit the so-called "absorption-brushes," a pair of dark diverging brushes upon a bright ground. These are due to the fact that for rays but slightly inclined to an optic axis the direction of vibration of the light, and therefore also the absorption, varies very greatly with the direction of the ray. The effect is well shown by some of the crystals from the Knappenwand, which are flattened parallel to C. A similar effect is shown by other crystals possessing very marked absorption, such as andalusite and magnesium platino-cyanide.

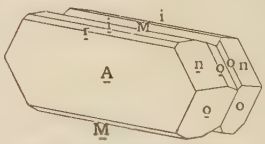


Fig. 698.—Epidote twinned on (100).

The darkest varieties of epidote, which also contain most iron, fuse most easily, and yield a magnetic slag. The faces A and C of Figs. 696, 697 are by most authors called T and M (C is denoted by M in Fig. 698) respectively.

An epidote containing very little iron, and corresponding to the formula given above, has been distinguished as **clinozoisite**.

A Noteworthy Locality:

Knappenwand (Untersulzbachthal, Salzburg).—Magnificent dark green crystals with the faces of Figs. 696 and 697 occur on massive or fibrous epidote in cavities of an epidote-schist. The associated minerals are white adularia, glassy apatite, and finely fibrous or hair-like green asbestos, also drusy calcite and titanite. The crystals are mostly twinned; B is quite small and sometimes rough.

Zoisite is the name given to an orthorhombic mineral having the same composition as an epidote poor in iron; at the Ducktown Copper Mines in Tennessee it is found in grey prisms with chalcopyrite, quartz, pyrites, and blende; the positive acute bisectrix ($2E = 50°$) emerges through (100), but the axial plane is sometimes parallel to (010), sometimes to (001).

Some of the angles of zoisite are nearly equal to some of epidote, and

[1] In Fig. 697 the edges between B and *o* should be parallel to those between *o* and *k*.

there is evidently a close relationship between the two minerals; possibly crystals of zoisite may be pseudo-symmetric growths formed by the intimate mimetic twinning of clinozoisite (*cf.* orthoclase and microcline, p. 519).

A beautiful massive red mineral, known as "thulite," which occurs with blue idocrase, garnet, epidote, and fluor in Telemark in Norway, and is used as an ornamental stone, is referred to zoisite. The colour is due to manganese.

VESUVIANITE

Vesuvianite.—Silicate of aluminium and calcium (with MgO, Fe_2O_3, and H_2O). Tetragonal (or pseudo-tetragonal ?); symmetry, holosymmetric.

$$a : c = 1 : 0{\cdot}5375.$$

C {001}, *m* {110}, A {100}, *p* {111}, *s* {311}.

pp (111) : ($\bar{1}$11) = 50° 40′, C*p* (001) : (111) = 37° 14′, A*s* (100) : (311) = 35° 9′, *ss* (311) : (131) = 45° 21′.

Cleavage A, *m*, imperfect. Brittle. Fracture, conchoidal. H = 6½; G = 3·41. Colour, green. Streak, white. Lustre, vitreous. $\omega = 1{\cdot}722$. Double refraction, very weak, (usually) negative; $\epsilon - \omega = -0{\cdot}001$. Pleochroic. Fusible (3) to a coloured glass. Scarcely affected by acids.

With the above description compare crystals from **Ala** (Piedmont).

Vesuvianite (or idocrase) is generally found in brown crystals (as at Christiansand in Norway), like Fig. 699. The above description relates

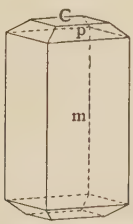


Fig. 699.—Vesuvianite, *m* {110}, *p* {111}, C {001}.

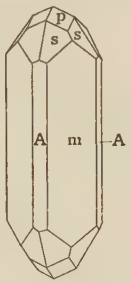


Fig. 700.—Vesuvianite, A {100}, *m* {110}, *p* {111}, *s* {311}, from Ala.

to the small green crystals (Fig. 700) found in the Ala valley, which are the best crystallised and the most transparent. The prism-faces of vesuvianite are vertically striated, and the basal plane is sometimes tesselated. The name is derived from the locality, Mount Vesuvius, where finely crystallised brilliant brown crystals are found. Here, as elsewhere, the vesuvianite may be distinguished from other minerals (garnet, etc.) which it may resemble, by a striated prism-zone perpendicular to a smooth basal plane. Twinning is unknown. Vesuvianite is one of the best examples of tetragonal crystallisation; it is mostly found in metamorphic limestone and crystalline schists, and as a contact-mineral.

Considerable variations in the angles, in the colour, in the optical properties, and in the composition, indicate that it may be an isomorphous mixture of two or more undetermined silicates. The crystals are often slightly biaxial; the birefringence of those from the river Wilui in Siberia is positive; there is often a division into sectors, to be observed in polarised light, and still more usual is a zonal growth of differently coloured material, or of bands which do not extinguish together. The axial angle in the biaxial zones may rise to 60°. The large prisms from the Wilui consist of wedges of two materials arranged hour-glass fashion; the two wedges which have the basal pinakoid for their bases are nearly uniaxial; those which extend laterally to the prism-faces consist of lamellæ having an axial angle of about 30°. Basal sections of vesuvianite generally have a quadrangular zonal structure. The mineral is probably to be regarded as pseudo-tetragonal, and composed of monoclinic sub-individuals. The dichroism is not very pronounced.

Most vesuvianite has approximately the following composition: $SiO_2 = 37$ to 39; $Al_2O_3 = 13$ to 16; $CaO = 33$ to 37; $Fe_2O_3 = 0$ to 6; $MgO = 1$ to 4; $H_2O = 0$ to 3.

In composition, vesuvianite is near to the lime-alumina-garnet, $Ca_3Al_2Si_3O_{12}$, containing in addition a little water (up to 3 per cent), which is given off at a red heat, and also frequently magnesium and alkalies; some analyses of vesuvianite have led to the formula $H_4Ca_{12}Al_6Si_{10}O_{43}$.

Some Noteworthy Localities:

Ala (Piedmont).—Here, at or near the place which yields the well-known specimens of garnet and diopside (p. 478), is found vesuvianite of two sorts: (1) beautiful green prisms rich in terminal faces, accompanied by chlorite, upon massive vesuvianite which traverses serpentine; (2) acute pyramidal, green, or brownish crystals (Fig. 700), accompanied by diopside and chlorite (with apatite) upon garnet, both crystallised and massive, which also traverses the serpentine. At another point in the same valley are found long thin striated prisms of a reddish-brown colour (wrongly called manganese-idocrase), accompanied by garnet, diopside, and chlorite upon garnet.

Monzoni (Tyrol).—Here, adjoining the Fassathal, in a bluish granular limestone, together with massive spinel and augite, are found yellow and greenish crystals of considerable size, of a pyramidal habit, form *p*. The vesuvianite is drusy and partly altered into steatite.

Vesuvius.—In the druses of the ejected limestone blocks of **Monte Somma** are found brilliant prisms of brown vesuvianite accompanied by garnet, both brown and yellow, green plates of meroxene, hornblende, sanidine, wollastonite, nepheline, etc. The vesuvianite is sometimes tabular, owing to the predominance of C {001}.

Christiansand (Norway).—Large brown crystals in calcite in the gneiss, associated with garnet. These are prisms with large basal plane and small pyramid faces, and show a zonal structure.

Achmatovsk (Urals).—Green and brown crystals in the chlorite-schist, or in calcite enclosed in the schist. Most of these are prismatic, but some of

the little green crystals are low pyramids, without prism-faces, terminated by small faces of the basal pinakoid, and of a habit so unusual for vesuvianite that they were formerly mistaken for sphene.

River Wilui (Siberia).—Large greenish-brown square prisms of the usual habit, known as "wiluite," occur in a tuff-like decomposed rock with green garnet and peculiar tetrahedral pseudomorphs known as "achtaragdite." The vesuvianite exhibits a remarkable tesselation on its faces.

PREHNITE

Prehnite, $H_2Ca_2Al_2Si_3O_{12}$, is an orthorhombic mineral which occurs under the same conditions as the zeolites, and is often associated with them; since, however, it only loses its water at a red heat, it can scarcely be classified with the zeolites.

Definite crystals are very rare, and the mineral has an extraordinary

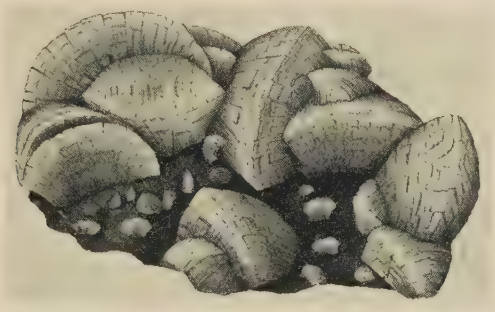


Fig. 701.—Prehnite from Bourg d'Oisans (British Museum).

tendency to appear in barrel-shaped or globular groups, as shown in Fig. 701, which can be seen, if carefully examined, to consist of rectangular plates; it is translucent, and of a pale green or grey colour. Distinct crystals somewhat resemble hemimorphite, and, like that mineral, are pyro-electric and therefore polar, but the polarity may be concealed by supplementary twinning (p. 100). The optical properties suggest that the prehnite is pseudo-rhombic. Prehnite is fusible (2) with intumescence to an enamel, and is decomposed by hydrochloric acid. Fine groups have been found near Bourg d'Oisans in Dauphiné (Fig. 701), associated with axinite, and accompanied by epidote, orthoclase, albite, and calcite, and sometimes enveloped by white asbestos.

AXINITE

Axinite, of which beautiful specimens occur near Bourg d'Oisans with the prehnite, is interesting crystallographically as a finely developed anorthic mineral, and chemically as a borosilicate (like tourmaline). The name, like that of sphene, refers to the wedge-like shape of the crystals

(ἀξίνη, an axe) (Fig. 702). The crystals are clove-brown in colour, transparent and brilliant, possessing a vitreous, almost adamantine, lustre. The common forms are M = {1$\bar{1}$0}, m = {110}, A = {100}, r = {1$\bar{1}$1}, s = {201}, x = {111}; the zones Mm and Mx are striated parallel to their edges; H = 6½; G = 3·28. Axinite is strongly pleochroic, optically negative, with weak birefringence ($\gamma - \alpha = 0{\cdot}009$), and has a large axial angle (2V = 74°) with very marked dispersion, $\rho < v$.

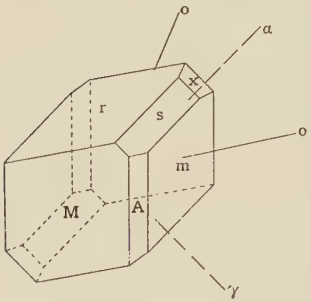


Fig. 702.—Axinite, A {100}, M {1$\bar{1}$0}, m {110}, s {201}, x {111}, r {1$\bar{1}$1}.

The composition is approximately $HCa_3Al_2BSi_4O_{16}$, where Ca is partly replaced by Fe and Mn.

Axinite fuses readily (at 2) with intumescence, and is not decomposed by acids. The presence of boron can be detected as in tourmaline.

Crystals very similar to those of Dauphiné occur in the cliffs at Botallack, near St. Just, Cornwall.

STAUROLITE

Staurolite has been mentioned above (p. 99) as one of the most striking examples of cruciform interpenetration-twinning, and to this its name alludes (σταυρός, a cross). It is an orthorhombic aluminium silicate somewhat resembling andalusite in composition, but containing about 16 per

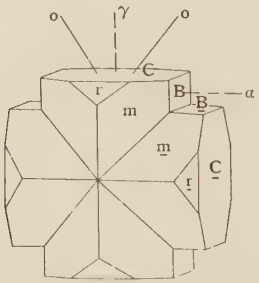


Fig. 703.—Staurolite, B {010}, m {110}, C {001}, r {101}, twinned on (032).

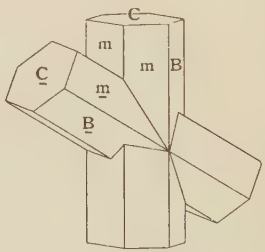


Fig. 704.—Staurolite twinned on (232).

cent of FeO and MgO, and less than 2 per cent of water, which is retained at a high temperature. Some analyses lead nearly to a formula $HFeAl_5Si_2O_{13}$, but the crystals are usually so impure that the composition has not been established with certainty; they are often partially altered to a steatitic substance, and contain quartz and other minerals. Sharply crystallised brown prisms—simple crystals like one arm of Fig. 703—occur in the white paragonite-schist of Monte Campione (Ct. Tessin), associated with cyanite,

and, as mentioned on p. 96, these are sometimes united in regular position with cyanite (Fig. 226); it is upon these crystals that the form and optical properties of the mineral may best be determined; $mm = (110) : (1\bar{1}0) = 50°\ 40'$; $Cr = (001) : (101) = 55°\ 16'$; hence $a : b : c = 0{\cdot}473 : 1 : 0{\cdot}683$; positive acute bisectrix perpendicular to C; axial plane (100); $2V = 88\frac{1}{2}°$; $\beta = 1{\cdot}75$; birefringence, rather weak, $\gamma - \alpha = 0{\cdot}01$; pleochroism very distinct; γ red, α and β yellow to green; but the colours seem to vary in different specimens. It is in the mica-schist of Brittany, at Quimper and other localities, that the well-known large twins (Figs. 703 and 704) are found; these are rough brownish crystals containing much quartz. In Fig. 703 the twin-plane is (032), and the arms of the cross are inclined to each other at 91° 22′; in Fig. 704 the twin-plane is (232), and the arms are inclined at 59° 34′; it is curious that neither the form {032} nor {232} is found as crystal-faces. Similar twins in loose isolated crystals are found in a decomposed mica-schist in Fannin County, Georgia, and here interpenetration-twins on (130) are also not uncommon.

THE CHLORITE GROUP

Chlorite Group.—Silicates of magnesia (or iron) and alumina, containing also about 12 per cent water, which is given off at a high temperature.

Monoclinic (pseudo-hexagonal). The crystals are hexagonal plates having their edges bevelled by faces inclined at various steep angles (60° to 80°) to the base.

The minerals are generally aggregates of small scales, and are mostly decomposition-products.

Cleavage, basal, perfect. Flexible. Dark green. Streak, white. Lustre, vitreous, pearly on (001). H = 2 to 3; G = 2·6 to 3·0. $\beta = 1{\cdot}58$. $\gamma - \alpha = 0{\cdot}01$. Different varieties may be uniaxial, biaxial, positive or negative. Pleochroic. Fusible with difficulty. Decomposed by sulphuric acid.

The minerals comprised in this group are all silicates of alumina and magnesia, and contain water, which is only given off at a red heat. In crystalline form they are very similar to the micas, occurring in hexagonal scales, which have a good basal cleavage. The chlorites are distinguished from the micas in being pliable and not elastic; their cleavage, moreover, is not so easy as that of the micas, and they are not so hard. Generally speaking, a soft pliable mineral which occurs in scaly aggregates, and is usually of a greenish colour, is to be referred to the chlorite group, but the name includes a large number of varieties which are not all well defined. They are, however, easily distinguished from the other minerals of scaly structure, such as mica and talc, since they contain a considerable amount of water; they do not contain any large proportion of alkalies like the former, and the alumina, which is an essential constituent of all chlorites, distinguishes them from talc. They resemble those minerals, however, in being monoclinic and pseudo-hexagonal; the refractive index is near that of talc and mica, but the weaker double refraction serves to distinguish chlorite from either; thin sections usually show no interference rings.

Two well-crystallised varieties are conspicuous among the specimens commonly to be found in collections, namely, pennine and clinochlore.

Pennine occurs in large dark green crystals at Zermatt, accompanied by a fibrous diopside in massive asbestos-schist, or " mountain leather " ; these crystals resemble long acute rhombohedra with rough faces terminated by the basal plane, to which they are inclined at an angle of about 76°. The cleavage-flakes are sometimes negative, sometimes positive, and may be either uniaxial or biaxial, but are generally the former. Pennine possesses a very remarkable pleochroism ; the colour of a section transverse to the cleavage is clear green when viewed by light vibrating parallel to the cleavage-trace ; yellow-brown or almost red when the light vibrates perpendicular to the cleavage.

Clinochlore occurs in green plates and in curved foliated sheaves in the cavities of a chlorite-schist at Achmatovsk in the Urals, where it accompanies beautifully crystallised garnet, diopside, and apatite. The hexagonal tables are bevelled by faces inclined at $71\frac{1}{2}°$ or 66° to the basal plane ; they are optically positive, and either biaxial with variable axial angle or sometimes uniaxial ; the pleochroism is similar to that of pennine, but less marked. The acute bisectrix is perceptibly inclined to the cleavage in the plane of the optic axes, so that, as indicated by its name, the mineral is distinctly monoclinic.

Very similar to the occurrence at Achmatovsk is that at Ala (Piedmont), where beautiful little green hexagonal plates accompany the garnet and diopside described on p. 478.

Two very striking chrome-chlorites of a deep rose-red colour from the Urals are known, and have received the names kämmererite and kotschubeite ; the first, being nearly uniaxial, has generally been regarded as a variety of pennine, and the latter as a variety of clinochlore.

Three varieties of the chlorite group are generally distinguished by their composition :

Pennine, the magnesia-chlorite, with about 35 per cent SiO_2.

Clinochlore, the intermediate chlorite, with about 30 per cent SiO_2.

Prochlorite, the iron-chlorite, with about 25 per cent SiO_2 and the magnesia largely replaced by FeO.

The name chlorite was given by von Kobell of Munich to the mineral from Zillerthal and Salzburg containing 27 per cent of SiO_2, while the more siliceous mineral from Achmatovsk (31 per cent) received the name " ripidolite " on account of its structure (ῥιπίς, fan). The name ripidolite was unfortunately transferred by Rose to the sheaf-like groups from St. Gothard, a mineral which contains about 25 per cent of SiO_2 and corresponds to von Kobell's chlorite, while he called the Achmatovsk mineral " chlorite." This has naturally led to considerable confusion in the nomenclature, and Dana's name **prochlorite** is therefore here used for the chlorite of Kobell.

The chlorites were formerly divided into three or more classes according to their optical characters, which were supposed to distinguish them into rhombohedral and monoclinic crystals ; a chemical classification was not then possible. But when biaxial crystals are interlaminated with their

axial planes at an angle with one another they may give rise to a compound crystal which is apparently uniaxial, and there can now be little doubt that all the minerals of this group belong to the monoclinic system, and that those which are apparently rhombohedral owe their form and their optical characters to the superposition of numerous twin-lamellæ, either of the same or of different varieties. This effect has already been mentioned in the case of the piles of mica plates described by Nörrenberg and by Reusch (pp. 205, 208).

The chlorites form overlapping twins of two kinds: (1) like those of mica (p. 531), (2) twins by rotation in the plane (001) (" pennine law "). In the latter the traces of the axial planes are parallel, but in the former they are inclined at angles of 120°, as in the piles of Reusch.

Now their extremely variable composition shows that the minerals of this group are doubtless mixtures of two or more distinct substances; it was shown by Kenngott that in all the analyses of chlorite, if the Al_2O_3 be replaced by a corresponding amount of the pyroxene silicate $MgSiO_3$, the composition is reduced to that of serpentine, and may be represented by the formula $H_4Mg_3Si_2O_9$. Consequently, Tschermak regards the chlorites as isomorphous mixtures in varying proportions of the two molecules—

(Serpentine), $H_4Mg_3Si_2O_9$ . . . Sp
(Amesite), $H_4Mg_2Al_2SiO_9$ . . At

The latter corresponds nearly to a chloritic mineral from Chester (Massachusetts), known as " amesite."

The composition of the three chlorites above mentioned will then be represented thus:

Pennine . . . $\left\{\begin{matrix}Sp_3At_2\\Sp\ At\end{matrix}\right.$
Clinochlore . . . $\left\{\begin{matrix}Sp_2At_3\\Sp_3At_7.\end{matrix}\right.$
Prochlorite . . .

If this theory of the chlorite group be confirmed, the group MgSi must here be considered capable of replacing the group Al_2, as in the pyroxenes.

For the more massive and minutely crystalline varieties (which Tschermak has classed together as " leptochlorites "), a more complicated composition must be assumed.

Chlorite occurs in large quantities as chlorite-schist, of which it is an essential and almost the only constituent; this is, for example, the matrix of the crystallised clinochlore at Achmatovsk. Otherwise, the chlorites are generally decomposition products of mica, garnet, pyroxene, amphibole, and felspar, and occur as an earthy substance filling cavities in schists and altered eruptive rocks of all sorts. Vesicular cavities in basaltic rocks are frequently filled with fine scaly chlorite. Many of the altered micas have received the name " vermiculite " owing to the manner in which they swell and curl before the blowpipe flame.

Another group of micaceous minerals is known as the **clintonite group,** or the "brittle micas"; they are more brittle than mica, which they closely resemble, being also monoclinic but pseudo-hexagonal with perfect basal cleavage, but they contain much less silica (16 to 30 per cent); they are harder than the chlorites (H = 4 to 6), and contain much less water. The most interesting mineral of this group is **margarite**, which has sometimes been known as "lime-mica." Margarite occurs in white scales of pearly lustre; the name is derived from *μαργαρίτης*, a pearl; H = 4, G = 3. Acute bisectrix nearly perpendicular to the cleavage; 2E large, near 120°. The composition of this mineral appears to be quite definite, $H_2CaAl_4Si_2O_{12}$. Margarite is a very frequent associate of corundum, as at the emery mines of Asia Minor and of Massachusetts; margarite and diaspore are the common alteration products of corundum.

SECTION XXIV

SILICATES (*Continued*)

BERYL

Beryl.—Silicate of beryllium and aluminium; $Be_3Al_2Si_6O_{18}$; BeO = 14·0, Al_2O_3 = 19·0; SiO_2 = 67·0.

Hexagonal; holosymmetric.

$$a : c = 1 : 0{\cdot}4989.$$

$m = \{10\bar{1}0\}$, $p = \{10\bar{1}1\}$, $u = \{20\bar{2}1\}$, $s = \{11\bar{2}1\}$, $v = \{21\bar{3}1\}$, C = {0001}.

$Cp\ (0001) : (10\bar{1}1) = 29°\ 56'$, $Cu\ (0001) : (20\bar{2}1) = 49°\ 2'$,
$Cs\ (0001) : (11\bar{2}1) = 44°\ 56'$, $pp\ (10\bar{1}1) : (01\bar{1}1) = 28°\ 54'$, $uu\ (20\bar{2}1) : (02\bar{2}1) = 44°\ 22'$,
$vv\ (21\bar{3}1) : (12\bar{3}1) = 18°\ 11'$, $mv\ (10\bar{1}0) : (21\bar{3}1) = 37°\ 49'$, $ms\ (10\bar{1}0) : (11\bar{2}1) = 52°\ 17'$.

Cleavage C, imperfect. Brittle. Fracture, conchoidal. H = $7\frac{1}{2}$; G = 2·7. Bluish green. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}589$. Birefringence, weak, negative; $\epsilon - \omega = -0{\cdot}007$. Fusible with difficulty ($5\frac{1}{2}$). Insoluble in acids.

With the above description compare crystals from **Ekaterinburg** (Urals).

Beryl in its pale green varieties, known as aquamarine, and the dark green varieties, known as emerald, is familiar as a precious stone; fine specimens of beryl are found in the pegmatitic veins of some granites, while emerald has been found in slate and limestone in Colombia, and in schist at Takovaya in the Urals, the locality from which come the twins of alexandrite mentioned on p. 442.

Beryl is among minerals the best, and almost the sole example of holosymmetric hexagonal symmetry.

Beautiful little pale green crystals from Nerchinsk present excellent material for measurement; they are very bright and rich in faces and zones. Fig. 705 represents a common combination, but here and at other localities the crystals are sometimes a simple combination of prism and basal pinakoid, with perhaps one pyramid-form, such as *p* or *s*. The prism-faces are almost always striated vertically.

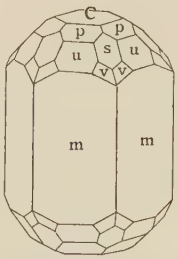


Fig. 705.—Beryl, *m* {10$\bar{1}$0}, *p* {10$\bar{1}$1}, *u* {20$\bar{2}$1}, *s* {11$\bar{2}$1}, *v* {21$\bar{3}$1}, C {0001}.
(Compare Fig. 170.)

Although the angles betray no deviation from hexagonal symmetry, and twinning is unknown, yet the crystals are frequently biaxial in parts; this may be due to strain.

The ordinary beryl found in pegmatite is generally in striated prisms without terminations; massive beryl may resemble apatite; it has, for example, been several times described as occurring in the augite-syenite of South Norway, but on nearer investigation the mineral has always proved to be apatite. Beryl can be distinguished from apatite by its superior hardness and inferior cleavage.

The rich green colour of the emerald is almost certainly due to traces of chromium; in hardness and refractive power it is inferior to most gem stones; the specific gravity and refractive index are such as to render the variously coloured aquamarines and emeralds easy of determination by means of methylene iodide and the total reflectometer. Flawless crystals of emerald are extremely rare.

Some Noteworthy Localities:

Ekaterinburg (Urals).—At **Mursinka** and other localities in this district,

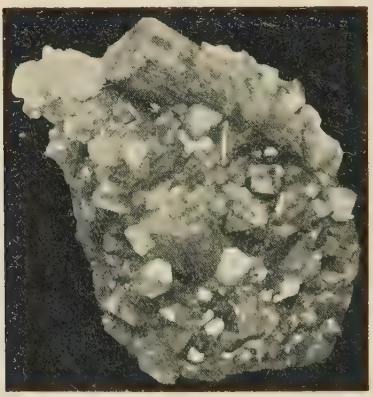


Fig. 706.—Beryl with Topaz from Adun-Chilon (British Museum).

in druses of the coarse granite, with topaz and black tourmaline, are found beautiful crystals of green, blue, or yellow colour, either a simple combination of $C m$, or $C m$ with p and s (Fig. 175, p. 72), or complex combinations like Fig. 705.

Nerchinsk (Transbaikal).—Very similar crystals, only more striated, are found with topaz and smoky quartz in the granite. At both localities are sometimes found drusy crystals deeply etched and rounded into pyramidal terminations. Neither natural nor artificial etching, however, has indicated anything less than holosymmetry in the mineral.

Fig. 706 represents a striated prism of ordinary beryl associated with topaz from **Adun-Chilon** in this district.

Elba.—In druses of the tourmaline-granite of **San Piero** (p. 541) are found richly terminated beryls with predominant basal pinakoid, colourless or tinted either red, green, or blue.

Mourne Mountains (County Down, Ireland).—Fine blue prisms, Cm, are found in druses of the albitic granite with orthoclase, topaz, and smoky quartz (Fig. 707); these have generally a zigzag zonal structure, indicative of pyramid-faces, near the end.

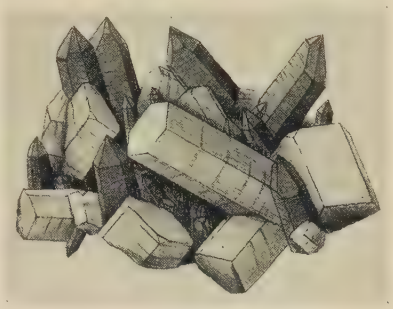


Fig. 707.—Beryl with Smoky Quartz and Orthoclase from the Mourne Mountains.

Muso (Colombia).—From this locality have been brought since the sixteenth century the beautiful deep green emeralds of the jewellers' trade. They occur as prisms (Cm, etc.) in a black bituminous limestone which contains ammonites, and are accompanied by white calcite, clear rock-crystal and black dolomite, together with crystals {210} of iron pyrites. A rare carbonate of cerium, known as parisite, is also found here in brown hexagonal pyramids. The emerald crystals are often fractured and re-cemented by calcite.

The names beryl (*βήρυλλος*) and emerald (*σμάραγδος*) are ancient names of unknown signification.

THE GARNET GROUP

Garnet.—$R''_3R'''_2(SiO_4)_3$, where $R'' = Ca$, Mg, Fe, Mn; $R''' = Al$, Fe, Cr. Cubic. H = 7; G = 4·1. Dark red. Streak, white. Common form, dodecahedron and {211}. Cleavage {110}, imperfect. Brittle. Fracture, uneven. Lustre, vitreous to greasy. Translucent; $\mu = 1·8$.

With the above description compare almandine from **Alaska.**

The following varieties of garnet are distinguished:

	G	H	μ	
Grossular, $Ca_3Al_2(SiO_4)_3$	3·5	<7	1·73	fusible (3); pale green or red.
Pyrope, $Mg_3Al_2(SiO_4)_3$	3·7	>7	1·70	fusible (>3); dark red.
Spessartite, $Mn_3Al_2(SiO_4)_3$	4·2	>7	1·80	fusible (3); brownish red.
Almandine, $Fe_3Al_2(SiO_4)_3$	4·25	>7	1·83	fusible (3); red.
Uvarovite, $Ca_3Cr_2(SiO_4)_3$	3·4	=7	1·84	infusible (6); green.
Andradite, $Ca_3Fe_2(SiO_4)_3$	3·8	<7	1·89	fusible (3); yellow, green, black.

All the garnets are isomorphous mixtures of the above, so that colour and composition are very variable. All except uvarovite are decomposed with difficulty by hydrochloric acid, andradite the most easily; ferriferous garnets fuse to a magnetic globule.

Garnet (Germ. *Granat*, Fr. *grenat*).—The garnet group includes an extremely well-defined series of minerals, comprised under the above general formula $R''_3R'''_2(SiO_4)_3$, and recognised by the dodecahedral or icositetrahedral form, strong refraction, somewhat greasy lustre, imperfect cleavage, and (except in uvarovite) ready fusibility.

Garnet occurs most commonly in the crystalline schists, gneisses, and granulites, or as a constituent (grossular) of lime-silicate hornfels; also as an occasional accessory constituent (andradite) of the alkaline basic rocks, such as phonolite and leucitophyre. In these rocks the garnet usually occurs in grains. In microscopic sections it is recognised by its square or hexagonal outline, strong refraction, absence of cleavage, and isotropic or nearly isotropic character.

One remarkable rock of which garnet is an essential and important constituent is eclogite, which consists of green hornblende ("smaragdite"), green augite ("omphacite") and garnet; this rock occurs at the Saualpe in Carinthia.

Garnet sometimes occurs in such large masses, associated with hornblende and magnetite, among the crystalline schists as to constitute a

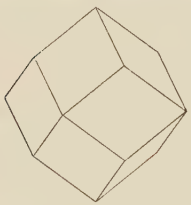


Fig. 708.—Garnet, {110}.

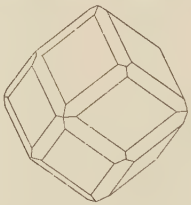


Fig. 709.—Garnet, {110}, {211}.

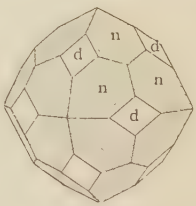


Fig. 710.—Garnet, *n* {211}, *d* {110}.

garnet-rock. It is also found (pyrope and "demantoid") in serpentines and peridotites, and (almandine and spessartite) in granite.

Generally speaking, the lime-alumina-garnets are found as secondary minerals in metamorphic rocks (especially limestones); the iron-alumina-garnets in granitic and gneissic rocks and schists; the manganese-alumina-garnets in granitic rocks; the magnesia-garnets in serpentine rocks; while the lime-iron-garnets are of widespread occurrence.

The finely crystallised specimens of museums come mostly from crystalline schists or from metamorphic limestones.

The garnets are essentially dodecahedral in habit; all the common crystals of garnet are either simple dodecahedra (Fig. 708) or dodecahedra *d* with their edges truncated by the icositetrahedron *n* {211} (Figs. 709, 710, 712). In these the faces of *n* are striated parallel to their intersections with *d*. Sometimes the dodecahedron-edges are also bevelled by {321}, whose faces replace the edges *nd* of Fig. 710.

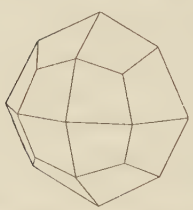


Fig. 711.—Garnet, {211}.

The simple icositetrahedron {211} is a characteristic form of the crystals from the river Wilui and from some other localities (Fig. 711).

Although the mineral is almost invariably dodecahedral, other forms are of course possible; simple white or yellow *octahedra* have been found in Elba; but, as a rule, the only faces of importance are such as belong to the dodecahedral zones. Twinning is unknown.

Optically very few garnets are quite isotropic, but many, especially

the rock-forming crystals, are very nearly so; on the other hand, some garnets are apparently pseudo-cubic, and composed of interpenetrating sub-individuals, which are sometimes uniaxial and sometimes biaxial. The optical characters seem to be related to the form of the crystals, and Klein has distinguished four types of structure: (1) octahedral, in which four uniaxial individuals interpenetrate with their bases in the octahedron-faces; (2) dodecahedral, in which six biaxial individuals have each an acute bisectrix perpendicular to a dodecahedron-face with the optic axial plane parallel to the longer diagonal; (3) icositetrahedral, in which twelve uniaxial or biaxial individuals have each an axis or acute bisectrix perpendicular to an icositetrahedron-face; (4) topazolitic, in which twenty-four biaxial individuals interpenetrate.

In view of the dependence of the optical anomalies of garnet upon the external form of the crystals, some authors consider that they are caused by strain, as in unannealed glass or the gelatine models mentioned on p. 205, and are not the result of pseudosymmetry. In minerals like the garnets, which are usually mixtures of two or more isomorphous substances, such strains might well be supposed to occur owing to a difference in the dimensions of the lattices of the components, corresponding to a difference in their molecular volumes. In favour of this view is the observation of Brauns that crystals of pure ammonia-alum, or of pure lead nitrate, are isotropic, while those which contain an admixture of potash-alum, or of barium nitrate, are birefringent and show optical anomalies resembling those of the garnets.

Grossular, lime-alumina-garnet (from *grossularia*, a gooseberry, in allusion to the green colour of some varieties).

$SiO_2 = 40{\cdot}0$, $Al_2O_3 = 22{\cdot}6$, $CaO = 37{\cdot}4$, generally containing also iron, manganese, and magnesium in small quantities.

Some Noteworthy Localities:

Ala (Piedmont).—In the cavities of a massive red grossular traversing serpentine at the head of the Ala valley. This valley lies in the zone of schists, serpentines, and gabbros which surround the granitic gneiss of the Graian Alps.

The garnet (so-called hessonite or cinnamon-stone) occurs in brilliant hyacinthine-red dodecahedra with {211} {321}, associated with crystals of green diopside, vesuvianite, and chlorite, forming one of the most beautiful mineral associations to be found in collections (see p. 478).

Monzoni (Tyrol).—In veins at the contact of crystalline limestone with augite-syenite; green and yellow icositetrahedra {211}, sometimes with vesuvianite and calcite (see p. 558).

Vesuvius.—In the ejected blocks of **Monte Somma** lustrous yellow or brown crystals {110}, or {110} and {211}, with idocrase, wollastonite and green meroxene (see p. 537).

Jordansmühl (Silesia).—*Colourless* glassy dodecahedra on massive prehnite in serpentine.

Achtaragda River (Siberia).—Green *icositetrahedra* with vesuvianite and "achtaragdite" in a volcanic tuff (see p. 559).

Cziklova (Hungary).—Brown and yellow dodecahedra, sometimes with *cube*-faces, in massive blue calcite.

Telemark (Norway).—*White* greasy dodecahedra with blue vesuvianite (cyprine), thulite, fluor and quartz ; these garnets contain manganese.

Pyrope (*Böhmischer Granat*), magnesia-alumina-garnet (from πυρωπός, fiery-eyed).

$SiO_2 = 44{\cdot}7$, $Al_2O_3 = 25{\cdot}3$, $MgO = 30{\cdot}0$, containing also iron and calcium. Blood-red ; fusible with difficulty. This is the mineral which supplies the common red garnet of jewellery.

Some Noteworthy Localities :

Meronitz (Bilin, Bohemia).—Angular grains in a conglomerate of marl, serpentine, granulite, gneiss, etc. The pyrope is enclosed in the serpentine, which is itself an alteration product of olivine, and it may therefore have been originally a constituent of a rock of the nature of eulysite. Some of the grains have the form of rough *cubes*.

South Africa.—Red angular grains accompanying the diamond in the serpentinous conglomerate known as " blue ground," and found also in the river washings ; these are also sometimes of cubic habit.

Spessartite, manganese-alumina-garnet.

$SiO_2 = 36{\cdot}4$, $Al_2O_3 = 20{\cdot}6$, $MnO = 43{\cdot}0$, always containing also much iron (FeO).

Some Noteworthy Localities :

Aschaffenburg (Spessart, Bavaria).—Yellow to red icositetrahedra in granite.

Haddam (Connecticut).—Large red masses in granite.

Belgium.—In granules in the hone-stones of the Ardennes, and in a black metamorphic quartzite from **Bastogne**.

Nathrop (Colorado).—Bright isolated reddish-brown icositetrahedra occur with topaz in the cavities or lithophyses of a banded rhyolite.

Almandine (precious garnet), iron-alumina-garnet (the name is a corruption of Pliny's *alabandicus*).

$SiO_2 = 36{\cdot}2$, $Al_2O_3 = 20{\cdot}5$, $FeO = 43{\cdot}3$, generally contains also calcium, magnesium, and manganese.

Some Noteworthy Localities :

St. Gothard (Switzerland).—Red and brown dodecahedra and icositetrahedra in mica-schist and gneiss.

Fahlun (Sweden).—Red dodecahedra, in chlorite, associated with iron and copper ores.

Ceylon and **India.**—Nodules used for jewellery. When cut *en cabochon* these are known as " carbuncles."

Botallack (St. Just, Cornwall).—Red icositetrahedra in the hornblende-schist of the cliffs.

Fort Wrangell (Alaska).—Beautiful red dodecahedra truncated by {211} occur here in a mica-schist (Fig. 712) ; these crystals are remarkably symmetrical.

Almandine generally has a somewhat characteristic purplish-red colour; it is used considerably in jewellery, often cut *en cabochon* with a rounded surface. Under the microscope almandine is usually seen to contain very fine hair-like fibres of some mineral, and it always yields, when viewed with a spectroscope, the characteristic absorption spectrum of Fig. 473, p. 335.

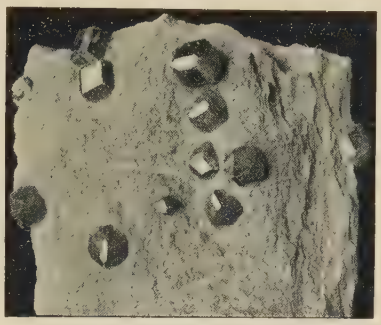


Fig. 712.—Almandine on Mica Schist from Alaska.

Uvarovite, lime-chrome-garnet (named after a Russian minister).

$SiO_2 = 36{\cdot}0$, $Cr_2O_3 = 30{\cdot}4$, $CaO = 33{\cdot}6$, containing also aluminium and iron. Green; infusible.

Some Noteworthy Localities:

Bisersk (North Urals).—Small, brilliant, emerald-green dodecahedra in cavities in chromite.

Orford (Canada).—Small dodecahedra in granular limestone with pyroxene.

Andradite, lime-iron-garnet (named after a Portuguese mineralogist).

$SiO_2 = 35{\cdot}5$, $Fe_2O_3 = 31{\cdot}4$, $CaO = 33{\cdot}1$, generally containing also aluminium and magnesium ("common garnet"); the black variety ("melanite") contains titanium.

Some Noteworthy Localities:

Ala (Piedmont), at the Mussa Alp, near the hessonite locality. Beautiful honey-yellow and green dodecahedra in cavities of a massive greenish pyroxene (so-called "mussaite") which traverses the serpentine. This garnet is known as "topazolite."

Rome.—At **Frascati** loose black dodecahedra with truncated edges, doubtless derived from the piperno of the **Alban Mountains.** These are known as "melanite."

Pyrenees.—Small black dodecahedra ("pyreneite") in a dark-coloured limestone; these show a zonal structure under the microscope, and are biaxial in parts.

Sisertsk (Urals).—Bright green nodules with chrysotile, dolomite, and magnetite in a serpentinous rock. A similar green garnet in rolled fragments is also found at **Nizhni-Tagil.** These are known as "demantoid." This beautiful mineral is cut as a gem stone, and is commonly sold as "olivine."

Arendal (Norway).—Brown dodecahedra in calcite among the magnetite deposits.

ZIRCON

Zircon.—Silicate of zirconium; $ZrSiO_4$; $ZrO_2 = 67{\cdot}2$, $SiO_2 = 32{\cdot}8$.

Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}640.$$

$$p = \{111\},\ A = \{100\},\ m = \{110\},\ x = \{311\}.$$

$$pp\ (111) : (1\bar{1}1) = 56°\ 40',\ mp\ (110) : (111) = 47°\ 50'.$$

Cleavage {110}, {111}, imperfect. Brittle. Fracture, conchoidal. H = 7½; G = 4·7. Brown. Streak, white. Lustre, adamantine. Translucent; ω = 1·931. Birefringence, strong, positive; $\epsilon - \omega = 0{\cdot}062$. Infusible. Insoluble in acids.

With the above description compare crystals from **Miask** in the Urals.

Zircon is isomorphous with the oxides, cassiterite and rutile, and for this reason is often placed in the same group with them among the oxides. It is an important (accessory) rock-constituent, especially in the more acid eruptive rocks, and having been one of the earliest minerals to solidify, is always in crystals; it is found in crystals of considerable size in elæolite-syenite and augite-syenite, and in small or microscopic crystals in a great variety of igneous rocks, and in the crystalline schists, and especially in gneiss. Being little liable to decomposition, it is often found in small crystals in sands and other materials derived from the destruction of any

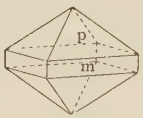


Fig. 713.—Zircon, *m* {110}, *p* {111}.

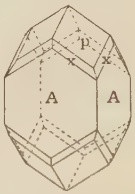


Fig. 714.—Zircon, A {100}, *p* {111}, *x* {311}.

of these rocks; it is common among the heavy constituents of auriferous and gem sands.

Zircon crystals are almost always a combination of a square prism, or of the two square prisms A, *m*, with a square pyramid, the habit being either pyramidal, as in Fig. 713, or more prismatic, as in Fig. 714; in microscopic crystals usually the latter. A large development of the form *x* sometimes gives them an acute termination.

Zircon is one of those minerals, like quartz and cassiterite, on which the basal plane is very rarely developed.

The close resemblance between zircon and the rutile group is displayed in their angles (*pm* (111) : (110) is 47° 50′ for zircon, 47° 40′ for rutile, 46° 27′ for cassiterite) as well as in their structure (p. 416). This resemblance is shared by another mineral of analogous composition, which is neither oxide nor silicate, namely, the rare phosphate xenotime, so that the following series must be regarded, if not as isomorphous in the strict sense, at least as "isotypic".

Cassiterite	$SnSnO_4$
Rutile	$TiTiO_4$
Zircon	$ZrSiO_4$
Thorite	$ThSiO_4$
Xenotime	YPO_4

It was always a matter of surprise that zircon did not twin, like rutile, on (101), until about the year 1881 crystals like Fig. 715 were found in

a crystalline limestone in Renfrew County, Ontario (Canada,) which are twinned, and on this very law.

Zircon is recognisable under the microscope by its very high refraction and birefringence ; when mounted in Canada balsam it exhibits a marked relief, and in ordinary rock sections gives interference-tints of the third or higher orders. A basal section of a zircon crystal rarely gives a normal uniaxial figure, the black cross being broken into hyperbolic brushes. Some accordingly regard the crystals as mimetic twins of monoclinic individuals ; the effect is often associated with well-marked zonal structure.

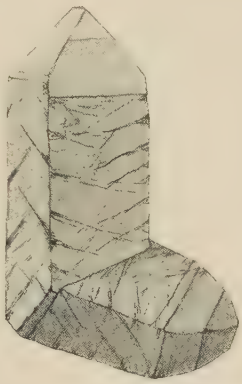


Fig. 715.—Zircon twinned on (01$\bar{1}$), from Ontario.

Its hardness, high refractive index, and great dispersion render zircon a valuable gem ; in refraction and dispersion it comes next to the diamond among precious stones ; it further possesses a very great range of colour. The ordinary crystals are dark brown, but even among the clear varieties suitable for gems are to be found also colourless stones, and various shades of orange, yellow, red (jacynth), pale green and grey (jargoon). The colour is frequently changed or lost on heating. In some varieties it may be due to a trace of Fe_2O_3, as it can be altered by heating in the oxidising or reducing flame. The specific gravity of zircon varies between 4·7 and 4·0, and is in most cases increased by heating. Three varieties have been distinguished : (1) G = 4·7 (unchanged on heating), (2) G = about 4·3 (increased on heating to not more than 4·7), (3) G = 4·0 (unchanged on heating). The first two of these may be different modifications of the same substance ; the third may possibly be a distinct mineral ; it differs from the others in having weak birefringence.

Some specimens of zircon contain uranium and thorium, and most are radio-active.

The small crystals of zircon in rocks, when enclosed in coloured minerals such as biotite or tourmaline, are usually surrounded by a small circular area of darker colour and strong pleochroism. These " pleochroic haloes " have been shown by Joly to be caused by the radio-activity of the zircon. The haloes are spherical in shape, and their radius varies with the nature of the enclosing mineral (and of the inclusion) ; it represents the range of penetration of the α-particles, to which the colour-change is due, in the mineral in question (*cf.* p. 220). The diameter of such haloes varies up to 0·04 mm.

Zircon is, as mentioned on p. 335, one of the minerals which gives a characteristic absorption-spectrum (Fig. 472) ; this appears to be almost constant for zircons of different colours ; it may be due partly to uranium.

Although very stable, and only attacked with difficulty by hot sulphuric acid, zircon is liable to hydration in nature, and several altered varieties which have acquired a vitreous or greasy lustre are known by special names.

Among characteristic occurrences may be mentioned those of Fredriksvärn and similar localities in Norway, where zircon is a constituent of the "zircon-syenite" in crystals of the habit of Fig. 714, associated with orthoclase, elæolite, etc.; the Ilmen Mountains in the Urals, where it occurs in crystals of prismatic habit in veins of the granite, associated with orthoclase, mica, apatite, etc. Colourless zircon is found in small crystals in drusy cavities in the trachytic ejections of Laach in the Eifel; also in beautiful crystals, like Fig. 714, associated with pink titanite and chlorite in the Pfitschthal in the Tyrol. From Ceylon come fine gem stones.

SECTION XXV

THE PHOSPHATES, ARSENATES, ETC.

THE APATITE GROUP

Apatite.—Fluo-phosphate of calcium; $Ca_5F(PO_4)_3$; $CaO = 55{\cdot}6$, $P_2O_5 = 42{\cdot}2$, $F = 3{\cdot}8$.

Hexagonal; symmetry, hexagonal equatorial.

$$a : c = 1 : 0{\cdot}7346.$$

$$m = \{10\bar{1}0\},\ C = \{0001\},\ x = \{10\bar{1}1\},\ s = \{11\bar{2}1\},\ \mu = \{21\bar{3}1\}.$$

$$Cx\ (0001) : (10\bar{1}1) = 40°\ 18',\ Cs\ (0001) : (11\bar{2}1) = 55°\ 45',$$
$$xx\ (10\bar{1}1) : (01\bar{1}1) = 37°\ 44',\ m\mu\ (10\bar{1}0) : (21\bar{3}1) = 30°\ 20',\ ms\ (10\bar{1}0) : (11\bar{2}1) = 44°\ 17',$$
$$mx\ (10\bar{1}0) : (01\bar{1}1) = 71°\ 8'.$$

Cleavage *m*, C, imperfect. Brittle. Fracture, conchoidal. $H = 5$; $G = 3{\cdot}2$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}646$. Birefringence, very weak, negative; $\epsilon - \omega = -0{\cdot}004$. Fusible with difficulty (5). Soluble in hydrochloric acid.

With the above description compare crystals from the **St. Gothard.**

Apatite is a widespread mineral of considerable scientific and commercial importance. It was distinguished from tourmaline, fluor, beryl, and chrysolite (minerals with which it had previously been confused) in 1775 by Werner, and was found by Klaproth to consist of phosphate of lime; the name is derived from *ἀπατάω*, I deceive. The presence of Cl or F as an essential constituent in apatite was first proved by Rose in 1827.

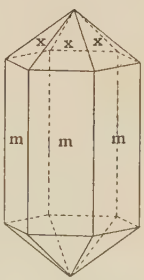


Fig. 716.—Apatite, *m* {10$\bar{1}$0}, *x* {10$\bar{1}$1}.

Large opaque crystals of apatite are found in metamorphic limestones; those from Canada are sometimes more than a foot in length. Such crystals may be of various shades of blue, green, yellow, or brown, and are generally simple combinations of prism and pyramid (Fig. 716), with or without the basal plane, and are often doubly terminated. Smaller but more perfect crystals occur in the druses of the crystalline schists, and with other fluoriferous minerals in the tin-bearing veins in granites. The most perfect crystals are the little limpid prisms from the St. Gothard, which exemplify the hexagonal (not di-hexagonal) symmetry of the mineral

(Fig. 717). Here the edges between m and C are replaced by a series of pyramids, and each corner may bear a face of the form s; but besides these are generally found one or more faces, such as μ, in the zone msx, lying between m and s. These faces, though present at both ends of the crystal, are situated on one side alone of the prism-edge. In this they differ from the trapezohedral faces of quartz, which lie on opposite sides of the prism-edge at the upper and lower ends of the crystal (Fig. 198, p. 79).

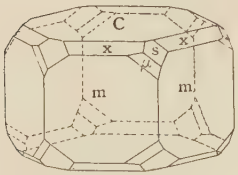


Fig. 717.—Apatite, m {10$\bar{1}$0}, C{0001}, x {10$\bar{1}$1}, s {11$\bar{2}$1}, μ {21$\bar{3}$1}.

Twins of apatite are almost unknown; but it has been stated that some apparently holosymmetrical crystals are in reality supplementary twins.

The hexagonal equatorial symmetry of apatite is also made clear by etching with hydrochloric acid (Fig. 284, p. 126).

Ordinary apatite is distinguished from beryl by its inferior hardness and by its better cleavage.

Apatite in microscopic crystals is a very widespread constituent of igneous rocks of all sorts; it generally occurs in long hexagonal prisms or needles, which have been one of the first minerals to crystallise; they can

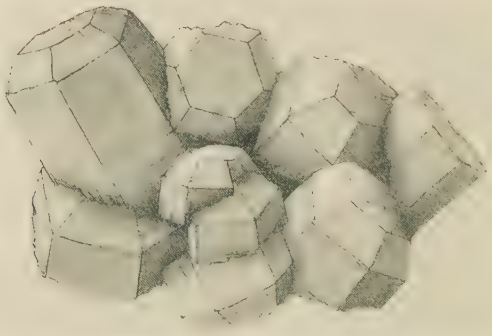


Fig. 718.—Apatite (altered) from Norway.

be recognised by the imperfect C-cleavage, the weak birefringence, and the fairly high refractive index.

Some apatite is biaxial with a small axial angle, but this peculiarity is not so marked as in the other members of the apatite group; it may sometimes be due to isomorphous intermixture with them.

From the chemical point of view two sorts of apatite are to be distinguished—fluor-apatite and chlor-apatite; the first corresponds to the formula given above, while in some varieties the fluorine is entirely replaced by chlorine; there are also intermediate varieties containing both chlorine and fluorine, which are to be regarded as isomorphous mixtures of the two. Of the pure compounds fluor-apatite is more

common than chlor-apatite ; some varieties contain small proportions of water due to the replacement of Cl and F by OH. On the other hand, several analyses have given a deficiency of Cl or F, and it has consequently been supposed that in these chlorine and fluorine have been replaced by oxygen. Expressed as an ortho-phosphate the formula of apatite is $Ca_4(CaF)(PO_4)_3$, and in this case the corresponding oxygen compound would be $Ca_8(Ca_2O)(PO_4)_6$. Almost pure chlor-apatites occur in Norway, where they constitute beds in a metamorphic limestone.

Massive apatite is mined on a large scale at Ödegaarden in Norway, where it occurs in veins consisting of apatite, hornblende, enstatite, and black mica in a gabbro which is rich in scapolite near these veins. The mineral is chlor-apatite. Apatite is very largely worked for use as a manure, but the materials mined for this purpose are mainly the massive, concretionary or earthy varieties, which occur in enormous quantities in several parts of the world ; these are white or pale-coloured amorphous deposits, and are totally unlike crystallised apatite in appearance. The impure massive phosphate is often known as " phosphorite." Many of these commercial phosphates are of organic origin ; the phosphatic nodules which occur in the Greensand of Cambridge and other places were formerly supposed to be the excreta of extinct reptilia ; but though probably of organic origin, they are usually nodular concretions due to the concentration of phosphatic material previously disseminated through the sand. A phosphate of lime of more recent organic origin is the " guano " found in vast deposits in Chili, Peru, Africa, etc.

Some Noteworthy Localities :

Knappenwand (Untersulzbachthal).—The most beautiful crystals of apatite yet discovered have been found here in cavities of an epidote- or chlorite-schist accompanied by fine dark green crystals of epidote, adularia, and a pale green hair-like asbestos. The apatite is limpid, of thick tabular habit, very rich in faces, and sometimes encloses the asbestos.

St. Gothard.—Little glassy crystals, like Fig. 717, very rich in brilliant faces, and showing very clearly the hexagonal (as contrasted with di-hexagonal) symmetry, occur in clefts of the granitic rock associated with adularia, albite, mica, and quartz.

Ehrenfriedersdorf (Saxony).—In the tin mines of the granite beautiful violet fluor-apatite occurs in druses of this rock accompanied by deep violet fluor, cassiterite, quartz, mispickel, and the yellowish micaceous mineral known as " gilbertite." The apatite is mostly in simple combinations, pinakoid $\{0001\}$ with the two prisms $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$, the prisms vertically striated ; small pyramid faces also occur. The apatite is sometimes banded with different shades of violet and green. Very similar crystals are found in the tin mines of **Schlaggenwald** in Bohemia with cassiterite, quartz, fluor, chalcopyrite, and earthy kaolin.

Luxullian (St. Austell, Cornwall).—The granite quarries have sometimes furnished brilliant bluish crystals of fluor-apatite ; these occur in druses of the white granite which are lined with kaolinised orthoclase and greenish gilbertite ; drusy purple fluor accompanies the apatite,

which is either in stout hexagonal tables or in long prisms, both habits displaying numerous pyramid-faces.

Jumilla (Murcia, Spain).—In cavities of a reddish decomposed volcanic rock associated with hæmatite and calcite, are pale greenish-yellow, rough prisms of apatite; these are often doubly terminated, generally without the basal pinakoid (Fig. 716), and exhibit the prism-faces $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$. This variety of apatite is known as "asparagus stone" (Germ. *Spargelstein*); it contains both fluorine and chlorine.

Burgess (Ontario, Canada).—In the limestone associated with the Laurentian gneiss here and in other parts of Canada, apatite is largely worked; it is accompanied by pyroxene, amphibole, titanite, zircon, garnet, etc. The dull bluish-green varieties of apatite are known as "moroxite." Prisms of this variety, sometimes doubly terminated (Fig. 716), are found embedded in a pink limestone at Burgess. A similar green moroxite is found in the limestone of **Arendal** (Norway).

The apatite group consists of the following members:

		c
Apatite	$Ca_4(CaF)(PO_4)_3$	0·735
Pyromorphite	$Pb_4(PbCl)(PO_4)_3$	0·736
Mimetite	$Pb_4(PbCl)(AsO_4)_3$	0·722
Vanadinite	$Pb_4(PbCl)(VO_4)_3$	0·712
Svabite	$Ca_4(CaF)(AsO_4)_3$	0·714

Pyromorphite.—Chloro-phosphate of lead; $Pb_5Cl(PO_4)_3$ or $Pb_4(PbCl)(PO_4)_3$; PbO = 82·3, P_2O_5 = 15·7, Cl = 2·6. Hexagonal; symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 40°\ 22'$. Cleavage *m*, *x*, imperfect. Brittle. Fracture, sub-conchoidal. H = 3½; G = 6·5. Liver-brown. Streak, white. Lustre, resinous. Translucent; $\omega = 2·06$. Birefringence, weak, negative; $\epsilon - \omega = -0·012$. Easily fusible (1½). Soluble in nitric acid.

With the above description compare crystals from **Ems** (Nassau).

Mimetite.—Chloro-arsenate of lead; $Pb_5Cl(AsO_4)_3$ or $Pb_4(PbCl)(AsO_4)_3$; PbO = 75·0, As_2O_5 = 23·2, Cl = 2·4. Hexagonal (pseudo-hexagonal ?); symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 39°\ 51'$. Cleavage *x*, imperfect. Brittle. Fracture, sub-conchoidal. H = 3½; G = 7·2. Yellow. Streak, white. Lustre, resinous. Translucent; $\omega = 2·15$. Birefringence, rather weak, negative; $\epsilon - \omega = -0·015$. Easily fusible (1). Soluble in nitric acid.

With the above description compare crystals from **Johanngeorgenstadt** (Saxony).

Vanadinite.—Chloro-vanadate of lead; $Pb_5Cl(VO_4)_3$ or $Pb_4(PbCl)(VO_4)_3$; PbO = 78·8, V_2O_5 = 19·3, Cl = 2·5. Hexagonal; symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 39°\ 26'$. Cleavage, none. Brittle. Fracture, uneven. H = 3; G = 6·8. Red. Streak, nearly white. Lustre, resinous. Translucent; $\omega = 2·35$ (red). Birefringence strong, negative; $\epsilon - \omega = -0·055$ (red). Easily fusible. Partly soluble in hydrochloric or nitric acid.

With the above description compare crystals from **Arizona.**

Pyromorphite (*πῦρ*, fire; *μορφή*, form) (Germ. *Grünbleierz*) was so named by Hausmann because when fused by the blowpipe the globule solidifies with facets; the mineral was known as a lead ore under the name of *Grünbleierz* or *Braunbleierz*. Klaproth first proved the green mineral from Zschopau in Saxony to be a phosphate.

Mimetite was not distinguished from pyromorphite until the analyses of Rose and Wöhler; the name (μιμητής, an imitator) was given in allusion to its resemblance to pyromorphite.

Vanadinite (Germ. *Vanadinbleierz*) from Mexico was first examined (1801) by Del Rio, who found it to contain a new element, to which he gave the name erythronium, and this was afterwards supposed to be chromium; it was not till 1830 that Wöhler showed this element to be identical with vanadium, which had then lately been discovered in Swedish iron.

These three minerals, with apatite, constitute a typical isomorphous series, each being capable of intermixture with the others; the isomorphism of vanadinite with pyromorphite led to the researches of Roscoe, which proved that oxide of vanadium is not VO_3 but V_2O_5, corresponding to P_2O_5.

They all occur in crystals which are usually a combination of hexagonal prism and basal plane, the edges being sometimes replaced by pyramid-faces; that the symmetry is hexagonal and not di-hexagonal has been shown by etching in the case of pyromorphite and mimetite, which both yield figures like those of Fig. 284, p. 126. Vanadinite is a mineral richer in faces, and sometimes shows $\{21\bar{3}1\}$ disposed like μ in Fig. 717, and so indicating the true symmetry of the mineral. Pyromorphite and mimetite are not rare minerals, since they are found in considerable quantities in the upper levels of many lead mines, where they have doubtless been derived from the alteration of galena. They range over a great variety of colour, especially different shades of brown, grey, green, and yellow; some orange-coloured varieties of pyromorphite are said to contain chromium, but other yellow and orange specimens (*e.g.* those from Scotland, Cumberland, and Cornwall) seem to be free from that element; some of the varieties containing lime, *i.e.* isomorphous mixtures with apatite, are pale brown or yellow, or even almost white. Isomorphous intermixtures of pyromorphite and mimetite are much more common; the pyromorphites from Cumberland contain about 9 per cent of As_2O_5. These two minerals are in fact difficult to distinguish except by chemical tests; the mining names, *Braunbleierz*, *Grünbleierz*, *Buntbleierz*, refer indiscriminately to both minerals and to their mixtures. They both possess the resinous lustre so characteristic of minerals containing lead. The presence of arsenic is indicated by the deposit obtained by heating a fragment of the mineral with charcoal in a closed tube, and the amount of arsenic serves to distinguish the two species. Both minerals give evidence of chlorine by the blue colour imparted to flame when heated in the oxidising flame in microcosmic salt which has been saturated with oxide of copper. The faceted globule yielded by the fusion of pyromorphite, and alluded to in its name, seems to be characteristic; the facets are not crystal faces. The test for arsenate or phosphate is best made by the ordinary methods with the nitric acid solutions of these two minerals.

Both pyromorphite and mimetite tend to form barrel-shaped crystals by aggregation and by the curvature of the prism faces. Many specimens of these minerals are in crystalline aggregates or in mamillary or con-

cretionary forms. Some of the varieties of pyromorphite containing lime are so persistently globular that they have received the name "polysphærite." The yellow, brown, and red mimetite found at Roughten Gill in Cumberland (Fig. 719) was for this reason called "campylite" (from *καμπύλος, curved*); it contains more than 3 per cent of P_2O_5.

A white mineral of resinous lustre found at Långban in Sweden and known as **hedyphane,** appears to be an isomorphous mixture of mimetite with pyromorphite, apatite, and an analogous *barium* compound; for it contains up to 8 per cent of BaO, and varying proportions of CaO. Crystals of this mineral have been found to have angles near those of the apatite group. That it is biaxial is no argument for excluding it from the group, for the other minerals exhibit so-called optical anomalies.

Pyromorphite is probably uniaxial when pure; mimetite is biaxial,

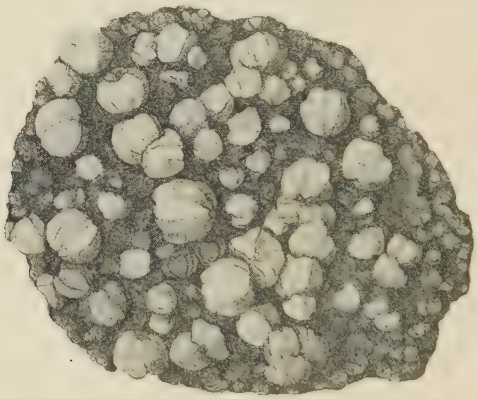


Fig. 719.—Mimetite (campylite) from Cumberland.

probably even when pure, and a basal section is seen to be composed of six triangular sectors. The mixtures of pyromorphite and mimetite are biaxial, and this property increases with the proportion of mimetite present, and may therefore be considered to be due to the latter. A basal section of such a mixture may be uniaxial in the centre and biaxial at the edges. It is probable that mimetite is pseudo-hexagonal like aragonite (p. 105); and possibly the other members of the group may also be so, but appear uniaxial owing to a more uniform and intimate interpenetration of the constituent crystals.

Some of the finest distinct crystals of pyromorphite are the large hexagonal prisms of dull violet colour found in the lead mines of Poullaouen in Brittany. These, as mentioned on p. 366, are sometimes altered into galena.

Brilliant pale green or yellow translucent crystals were formerly found lining cavities in a ferruginous vein-quartz at Huel Alfred near Camborne in Cornwall. Some of these are nearly pure mimetite.

Vanadinite has been found in lustrous red or yellow prisms in Mexico and in Arizona; these often bear pyramid-faces as well as the basal

pinakoid ; the crystals are sometimes hollow. The mineral can be identified by the colour, characteristic of vanadium, given to a bead of microcosmic salt.

A variety called "endlichite," found in brilliant orange- or lemon-yellow crystals at Lake Valley (New Mexico), contains from 11 to 13 per cent of As_2O_5, and may be regarded as an isomorphous mixture of vanadinite and mimetite.

Svabite, a rare mineral, only found in small colourless prisms at the manganese mines of Pajsberg and Nordmark in Sweden, appears to be the calcium arsenate, $Ca_4(CaF)(AsO_4)_3$, analogous to apatite ; it is further interesting as containing both Cl and (OH) partially replacing the fluorine.

A considerable number of phosphates are known as minerals, especially basic compounds ; they do not for the most part fall into isomorphous groups. The two best defined groups are those of olivenite and vivianite.

THE OLIVENITE GROUP

Olivenite is a copper arsenate formerly found in abundance in the copper mines of Cornwall, sometimes as olive-green orthorhombic prisms, {110}, {100}, {010}, terminated by the combination {101} {011}, which together resemble a square pyramid ; $(110) : (1\bar{1}0) = 86° 26'$.

It occurs more usually in fibrous aggregates of acicular crystals which often present a beautiful velvety surface. This variety is known as "wood-copper" (Germ. *Holzkupfererz*). Some specimens are quite soft and almost earthy. The colour of olivenite varies very widely through many shades of green, brown, and yellow, and the "wood-copper" is sometimes almost white. Composition $(CuOH)Cu(AsO_4)$, the water being given off only at a high temperature ; some As_2O_5 is replaced by P_2O_5.

To the same group with olivenite belong the following :

Libethenite	$(CuOH)Cu(PO_4)$.
Adamite	$(ZnOH)Zn(AsO_4)$.
Descloizite	$(PbOH)Pb(VO_4)$.

Libethenite is a mineral of the same forms and habit as olivenite, only of a darker green colour, which occurs in good crystals at Libethen in Hungary.

Adamite is found in crystalline crusts at the zinc mines at Laurium near Athens, which have furnished a number of interesting zinc minerals. It varies widely in colour owing to the presence of copper and cobalt, and may be white, yellow, red, blue, or green.

In olivenite, libethenite, and adamite, the axial plane is (001), and the axial angle about 80°, so that an optic axis is visible through each face of the prism {110}, and is nearly perpendicular to the face.

Descloizite occurs in small, lustrous, deep red, almost black, crystals

at Lake Valley (New Mexico), already mentioned as the locality of endlichite. Vanadium is partially replaced by arsenic and phosphorus, and lead by zinc and copper.

THE VIVIANITE GROUP

Vivianite, $Fe_3(PO_4)_2 . 8H_2O$, is a mineral belonging to the monoclinic system, which has been found in beautiful translucent steely indigo-blue prisms, *e.g.* in pyrrhotite at Wheal Jane, Truro ; the crystals have a highly perfect cleavage parallel to the plane of symmetry (010), and a pearly lustre on that face ; the lustre is vitreous on other faces. Vivianite is flexible and sectile. The obtuse negative bisectrix is perpendicular to the cleavage-face, and there is strong pleochroism. Analyses show the presence of Fe_2O_3, but this and the colour are due to subsequent oxidation, for at Delaware in Pennsylvania have been found *colourless* crystals containing only FeO and not Fe_2O_3, and these change their colour on exposure and become blue. Vivianite is also found as a blue earthy mineral. This earthy variety, which is of a paler colour than the crystals, occurs as a decomposition-product of other iron minerals accompanying fossils and organic remains ; it often gives a blue colour to bog-iron-ore and other ferriferous deposits.

To the same isomorphous group belong the corresponding arsenates of iron and cobalt, which are found crystallised, and probably also the corresponding arsenates of magnesium, nickel, and zinc, and the phosphate of magnesium ; but these latter are all too imperfectly crystallised to admit of measurement.

The arsenates of cobalt and nickel are fairly common minerals :

Erythrite, $Co_3(AsO_4)_2 . 8H_2O$, is a beautiful crimson mineral occurring in crystals like those of vivianite, with the same cleavage and flexibility, and the negative acute bisectrix perpendicular to the cleavage ; but it is usually found as a peach-coloured earthy mineral known as "cobalt bloom" (Germ. *Kobaltblüthe* or *Kobaltbeschlag*), corresponding to the earthy vivianite.

Annabergite, $Ni_3(AsO_4)_2 . 8H_2O$, is an apple-green mineral, found almost exclusively as the corresponding earthy "nickel bloom" (Germ. *Nickelblüthe*).

Erythrite and annabergite are the common decomposition-products of minerals containing cobalt or nickel, and are easily recognised by their characteristic colours, serving as certain indications of the presence of those metals.

Among the other hydrated phosphates the aluminium compounds wavellite and turquoise deserve mention.

Wavellite, $2(AlOH)_3(PO_4)_2 . 9H_2O$, belongs to the orthorhombic system, but almost always occurs in radiated aggregates giving rise to globular or botryoidal forms, Fig. 447, p. 307. The mineral is named after its dis-

coverer, Dr. Wavel, by whom it was found lining fissures in slate, near Barnstaple in Devonshire. It is translucent, and generally white or grey, but also assumes various shades of green, yellow, or brown. It is one of the best examples of radiated structure. Wavellite usually contains fluorine.

Turquoise or callaite (Germ. *Türkis*), $Al_2(OH)_3PO_4 . H_2O$, is only known as a massive mineral, as an incrustation, or in reniform nodules. The true oriental turquoise, valued in jewellery, is found in a brecciated porphyritic trachyte near Nishapur in Persia; together with limonite, the sky-blue turquoise fills cavities and crevices in this breccia, or is found as nodules in the decomposed rock. The name turquoise may be derived from "Turkey" through the French, or may be a corruption of the Persian name *Piruzeh*. Callaite is from *callais*—the name used by Pliny for a green stone brought from beyond India. It is probable that turquoise was always prized as a gem. In the turquoise of most localities the colour varies from sky-blue to pale apple-green. It has lately been found at several localities in New Mexico (Burro Mountains and Jarilla Mountains) as seams and nodules in trachyte. G = 2·7; H = 6.

In thin sections turquoise is seen to be not absolutely amorphous like opal, but to consist of very minute birefringent granules. The variations of colour are probably due to phosphate of copper or iron, either as an impurity or possibly in combination (*cf.* p. 613).

The true "oriental turquoise" is to be distinguished from another substance, known as "bone-turquoise" (*Zahntürkis*) or "occidental turquoise," also called "odontolite," and "*turquoise de la nouvelle roche.*" This, as its name signifies, is of organic origin, and consists of the teeth or bones of extinct mammals, stained probably by the absorption of earthy blue vivianite. It is, and has long been, used as turquoise. In thin sections it is seen to have an organic structure, and the colouring matter follows minute apertures. Bone-turquoise contains also $CaCO_3$, and effervesces with acids.

There are numerous phosphates and arsenates of copper, mostly of blue or green colour, which have been found accompanying the ores of copper in the Cornish and Utah mining districts, many of them beautifully crystallised. Among those which contain rare elements may be mentioned **torbernite** (or cupro-uranite), $Cu(UO_2)_2(PO_4)_2 . 8H_2O$ which resembles the vivianite group in composition. It is a beautiful mineral, occurring in vivid emerald-green square plates belonging to the tetragonal system, with a perfect basal cleavage. The corresponding calcium compound **autunite** (or calco-uranite) is very similar, but paler in colour, and is pseudo-tetragonal, giving a biaxial figure through the cleavage-plate.

The group also contains minerals in which the place of Cu or Ca is taken by Ba, and that of P by As.

All these minerals are strongly radio-active owing to the presence of uranium.

Monazite, the rare phosphate of cerium and didymium $(Ce,La,Di)PO_4$ (containing also thorium), which is now of great commercial importance as a source of the ceria and thoria required for incandescent gas mantles, is found in brown crystals of considerable size in the granite of Arendal in Norway, but the commercial material is obtained on a large scale in Brazil and North Carolina, from sands which are rich in grains of the mineral.

Monazite occurs in microscopic crystals, enclosed in the apatite of Arendal. These are left when the apatite is dissolved in nitric acid, and, like all monazite, may be identified by the absorption spectrum of Fig. 471, p. 334. Owing to the thorium present monazite is radio-active.

SECTION XXVI

THE SULPHATES

THE BARYTES GROUP

Barytes.—Sulphate of barium; $BaSO_4$; $BaO = 65{\cdot}7$, $SO_3 = 34{\cdot}3$.
Orthorhombic.

$$a : b : c = 0{\cdot}815 : 1 : 1{\cdot}314.$$

A = {100}, C = {001}, *m* = {110}, *d* = {102}, *o* = {011}, *y* = {122}, *z* = {111}.

mm (110) : ($1\bar{1}0$) = 78° 23′, C*d* (001) : (102) = 38° 51′, C*o* (001) : (011) = 52° 43′, C*z* (001) : (111) = 64° 19′, *oy* (011) : (122) = 26° 1′, *oz* (011) : (111) = 44° 18½′.

Cleavage C, *m*, perfect. Brittle. Fracture, uneven. H = 3; G = 4·5. Colourless. Streak, white. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}648$, $\beta = 1{\cdot}637$. Birefringence, weak, positive; $\gamma - \alpha = 0{\cdot}012$. Axial plane (010); acute bisectrix perpendicular to (100); $2E = 64°$, $\rho < v$. Fusible (3), with decrepitation. Not decomposed by acids.

With the above description compare crystals from **Dufton** (Westmorland).

Barytes, or heavy spar (Germ. *Schwerspath*), is a very common mineral in metalliferous veins, especially those containing lead, silver, and cobalt minerals, both as part of the veinstone and as crystals on the vein walls. It is remarkable that this sulphate, which is one of the most difficult substances to crystallise in the laboratory, should, as a mineral, furnish some of the most beautiful of crystallised specimens.

Commercially it is of considerable importance as the source of barium compounds, and as a white pigment ("permanent white"); for the latter purpose, however, it is mixed with white lead on account of its insufficient opacity.

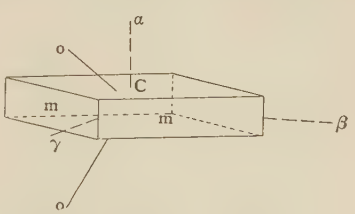


Fig. 720.—Barytes, *m* {110}, C {001}.

Barytes is easily recognised by its weight and cleavage (the name is derived from βαρύς, heavy). The cleavage-form C *m* (Fig. 720) is not unusual as a crystal combination, *e.g.* at Felsöbanya (*cf.* Fig. 723), but barytes is generally elongated in the direction of the *a*-axis, and bounded laterally by the form *o*, which is very common. The habit is variable—some crystals are elongated along the *b*-axis, and many are very rich in faces,

but they can always be correctly orientated by means of the cleavages; the C-cleavage is usually visible as pearly cracks giving the interference-tints of thin films.

Crystals elongated along the *c*-axis are so rare that when they were first discovered (at Betler in Hungary), they were supposed to be a new mineral, and received the name "wolnyn" (*cf.* Fig. 440, p. 304). Similar crystals have been found in Cornwall and in Virginia.

In most localities barytes is white and only translucent, and the crystals are often stained brown or red with oxide of iron; some of the transparent crystals are yellow, brown, or even blue.

The common barytes of the Derbyshire lead mines and many other localities is an aggregate of white, opaque, platy crystals, somewhat rounded and arranged in parallel groups. They resemble a flat rhombohedral combination. This barytes is generally known as "cawk." Another common variety is that known as "crested" or "cockscomb-barytes," generally rounded aggregations of tabular crystals like Fig. 720, with the acute prism-edges of the crystals projecting from the mass. Ordinary massive barytes is an opaque white material with a platy structure, the plates being often curved. All these, and even the radiated (Germ. *Strahlbaryt*) and columnar (Germ. *Stangenspath*) varieties, may be recognised by the weight and cleavage. The mineral also occurs as a white earthy substance. Crystals of witherite, for example, are often altered on the surface to white earthy or minutely crystalline barytes. The "Bologna stone," found as fibrous concretions in clay, near Bologna, attracted much attention at the beginning of the seventeenth century, when it was discovered that, after heating with charcoal, it possesses the property of becoming luminous in a dark room after exposure to the sun's rays. This was the first observation of inorganic phosphorescence. The property belongs to the barium sulphide, to which the mineral is reduced by heating with charcoal. It is noteworthy that the fibres of Bologna stone are elongated along the vertical axis; most fibrous barytes is elongated along the *a*-axis.

Some barytes, especially massive, possesses repeated twin-lamellæ parallel to *m* and *o*; the latter can be observed as striations on *m*, and sometimes give rise to an apparent cleavage parallel to *o*. It is believed that these are planes of secondary twinning due to pressure, for they are rarely observed in barytes which has crystallised out freely in veins or cavities.

Barytes is sometimes differently terminated at the two ends, and some observers have concluded from pyro-electric and etching experiments that it is polar; but the apparent polarity is exhibited along *both* the *a*- and the *c*-axis, and subsequent experiments with sodium carbonate and hydrochloric acid have yielded holosymmetric etched figures.

Barytes is generally fairly pure, but often contains a little strontium sulphate and calcium sulphate, the former doubtless owing to isomorphous intermixture with celestite. Before the blowpipe the barium is indicated by the green colour imparted to the flame, and the sulphur by the ordinary test after fusion with sodium carbonate on charcoal.

Although the mineral is for ordinary purposes insoluble in water, it has evidently been, in many instances, deposited by aqueous agency; thus near Nottingham it constitutes the cementing material of a sandstone, and it is sometimes deposited from mine waters containing barium chloride.

Some Noteworthy Localities :

Dufton (Westmorland).—Fine crystals have been found in the lead mines of this district, including some of the largest yet discovered. They are generally of the habit of Fig. 721, and are white, yellow, or brown. Some of these found in a mud were bounded on all sides by faces.

Liskeard (Cornwall).—Beautiful pale yellow crystals of tabular habit were formerly found in the silver-lead mines in this neighbourhood, associated with iron pyrites and fluor. They sometimes have prominent faces of {111}. Somewhat similar crystals were found in the copper mines of Gwennap.

Egremont (Cumberland).—Associated with the lustrous calcite found in hæmatite, are pale blue tabular crystals of barytes. Near Frizington have been found honey-yellow crystals elongated along the *a*-axis, and

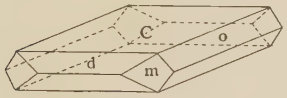


Fig. 721.—Barytes, C {001}, *m* {110}, *d* {102}, *o* {011}.

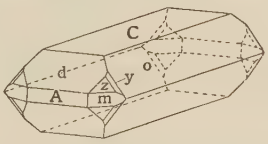


Fig. 722. — Barytes, C {001}, *d* {102}, A {100}, *o* {011}, *m* {110}, *z* {111}, *y* {122}.

somewhat rounded owing to the development of curved acute pyramid-faces nearly coincident with *o*. The basal pinakoid is striated parallel to *m*, and *m* is striated horizontally. Other crystals from here, which are tabular parallel to C and terminated by *m*, contain a brown nucleus of different habit, *viz.*, terminated by B and *m*.

Newhaven (near Youlgreave in Derbyshire).—Deep brown stalactitic barytes, with a radiating structure diverging from the axis of the stalactite. This also shows beautiful annular markings, and has been much used for ornamental purposes.

Nutfield (Surrey).—Beautiful honey-yellow crystals, doubly terminated, and of a habit similar to that of Fig. 722, are here found in Fuller's earth.

Felsöbanya (Hungary).—Fine tabular crystals, C, *m*, A, *d*, *o*, occur with stibnite, quartz, pyrites, blende, etc. They are either white or of various shades of blue and red, or are sometimes coloured yellow by impregnation with orpiment. These crystals are sometimes apparently polar in the direction of the *b*-axis, owing to the development of *m*, *z*, *y* on only one side. The barytes is sometimes penetrated by the needles of stibnite, as shown in Fig. 723.

The barytes group contains the following minerals :

Barytes	. $BaSO_4$.	$a : b : c = 0{\cdot}815 : 1 : 1{\cdot}314$
Celestite	. $SrSO_4$.	$0{\cdot}779 : 1 : 1{\cdot}280$
Anglesite	. $PbSO_4$.	$0{\cdot}785 : 1 : 1{\cdot}289$

Celestite.—Sulphate of strontium; $SrSO_4$; SrO = 56·4, SO_3 = 43·6. Orthorhombic.

$$a : b : c = 0{\cdot}779 : 1 : 1{\cdot}280.$$

$$C = \{001\},\ m = \{110\},\ o = \{011\},\ d = \{102\},\ l = \{104\}.$$

mm (110) : ($1\bar{1}0$) = 75° 50′, Cd (001) : (102) = 39° 25′, Co (001) : (011) = 52° 0′, Cl (001) : (104) = 22° 20′.

Cleavage C, perfect; m, good. Brittle. Fracture, uneven. H = 3; G = 3·9. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}624$. Birefringence, weak, positive; $\gamma - \alpha = 0{\cdot}009$. Axial plane (010). Acute bisectrix perpendicular to (100); 2E = 88° 38′. Fusible (3), with decrepitation. Insoluble in acids.

With the above description compare crystals from **Girgenti** (Sicily).

Anglesite.—Sulphate of lead; $PbSO_4$; PbO = 73·6, SO_3 = 26·4. Orthorhombic.

$$a : b : c = 0{\cdot}785 : 1 : 1{\cdot}289.$$

$$m = \{110\},\ C = \{001\},\ o = \{011\},\ d = \{102\},\ y = \{122\},\ z = \{111\}.$$

mm (110) : ($1\bar{1}0$) = 76° 17′, Cd (001) : (102) = 39° 23′, Co (001) : (011) = 52° 12′, yy (122) : ($1\bar{2}2$) = 89° 48′.

Cleavage C, m, fair. Brittle. Fracture, conchoidal. H = 3; G = 6·3. Colourless. Streak, white. Lustre, adamantine, inclining to resinous. Transparent; $\gamma = 1{\cdot}897$, $\beta = 1{\cdot}883$. Birefringence, positive; $\gamma - \alpha = 0{\cdot}020$. Axial plane (010). Acute bisectrix perpendicular to (100); $2V = 60°\ 50'$; $\rho < v$. Easily fusible ($1\frac{1}{2}$). Soluble with difficulty in nitric acid.

With the above description compare crystals from **Monte Poni** (Sardinia).

These sulphates constitute as perfect an isomorphous group as the corresponding series of carbonates, the aragonite group; but the sulphates are simpler in their crystallisation, being well developed orthorhombic crystals without pseudo-symmetry and devoid of twinning. They all occur in bright glassy crystals of tabular or prismatic habit, and are easily recognised by their three perfect cleavages, two {110} enclosing an angle of 76° to 78°, and being perpendicular to the third {001}; the orientation of the indicatrix is also the same for all the three minerals.

Barytes contains both calcium and strontium, and celestite may contain both barium and calcium, but the corresponding calcium sulphate, anhydrite (see p. 590), can scarcely be regarded as belonging to the same group on account of its difference of form and cleavage.

Although **celestite** (and anglesite), like barytes, occur in a very great variety of combinations, the common crystals are simple; celestite is generally elongated along the b-axis, while anglesite may resemble either barytes or celestite in habit, or may be elongated along the vertical axis. Both minerals occasionally occur in acute pyramidal crystals formed by pyramids of the type {khh} (usually {144} or {155}), which give them quite an unwonted appearance; examples are furnished by large crystals of celestite from Yate in Gloucestershire and from Virginia. Since the discovery of such crystals, it is generally believed that the acute pyramids consisting of granular calcite which have been found at various localities (the "barley-corn pseudomorphs" from Sangerhausen and the so-called

"jarrowite" from the Jarrow Docks in Durham and from the Clyde), about which there has been much discussion, are altered celestite.

The name celestite alludes to the bluish tint of the specimens (from Pennsylvania) first analysed by Klaproth in 1797. This colour is frequent in this mineral, *e.g.*, at Herrengrund, Salzburg, etc., and may be due to

Fig. 723.—Barytes, with Stibnite, from Felsöbanya.

a trace of iron phosphate. Celestite usually occurs in limestones or sandstones or associated with gypsum and rock-salt.

Celestite is of commercial importance as the source of strontium compounds, which are largely used for fireworks, etc., to produce red colours, and in sugar-refining. The strontium in the mineral is easily detected by the red coloration to flame, especially after the fused mass has been treated with hydrochloric acid and alcohol.

Some Noteworthy Localities :

Girgenti (Sicily).—Here colourless crystals, of prismatic habit owing to the predominance of *o*, like the barytes of Fig. 722, are situated upon sulphur or upon crusts consisting of acute rhombohedra of calcite.

Herrengrund (Hungary).—Beautiful blue crystals rich in faces occur in druses in the copper mines ; they are often situated upon pseudomorphs of calcite after aragonite ; the crystals are either prismatic, like Fig. 722, or rhombic plates, like Fig. 720.

Lake Erie.—On **Strontian Island** large crystals of the habit of Fig. 724 are found in the limestone.

Yate (Gloucestershire).—In the triassic marl are found geodes of celestite lined with large, transparent, colourless crystals both of prismatic and tabular habit. These are associated with and sometimes enclosed in gypsum crystals.

Anglesite is named from the locality where it was first found, the island of Anglesey. Here, at the Parys Copper Mine, small, doubly

terminated, yellow crystals of the habit of Fig. 725 were found in an earthy brown limonite.

But far finer specimens were subsequently found in the lead mines of Monte Poni in Sardinia, where the mineral has evidently been derived from the alteration of galena; it here occurs in lustrous, transparent, and colourless crystals lining cavities in a glistening granular galena.

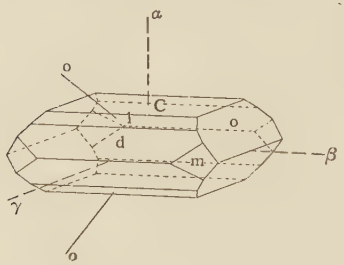


Fig. 724.—Celestite. C {001}, *o* {011}, *d* {102}, *l* {104}, *m* {110}.

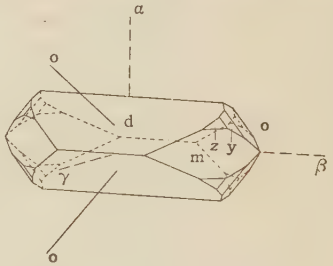


Fig. 725.—Anglesite. *m* {110}, *d* {102}, *o* {011}, *z* {111}, *y* {122}.

The crystals are of a great variety of combinations and habits, and are difficult to decipher without measurements of the angles.

Anglesite usually occurs in metalliferous veins as an alteration product of galena.

Two common characteristics of lead minerals distinguish anglesite from the other minerals of the group: its easy fusibility and adamantine or resinous lustre. The lead is easily detected in anglesite by reduction on charcoal; the mineral is an important ore of lead, and is found massive in large quantities in some mining districts.

ANHYDRITE

Anhydrite.—Sulphate of calcium; $CaSO_4$; $CaO = 41{\cdot}2$, $SO_3 = 58{\cdot}8$. Orthorhombic.

$$a : b : c = 0{\cdot}893 : 1 : 1{\cdot}001.$$

$$A = \{100\},\ B = \{010\},\ C = \{001\},\ m = \{110\},\ r = \{011\}.$$

$$mm\ (110) : (1\bar{1}0) = 83°\ 33',\ rr\ (011) : (0\bar{1}1) = 96°\ 30'.$$

Cleavage, A, B, C, perfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 2{\cdot}9$. Colourless. Streak, greyish. Lustre, vitreous to pearly. Transparent; $\gamma = 1{\cdot}614$, $\beta = 1{\cdot}576$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}043$. Axial plane (010). Acute bisectrix perpendicular to (100); 2E 71° 30′; $\rho < v$. Fusible (3). Soluble in hydrochloric acid.

With the above description compare crystals from **Stassfurt** (Prussia).

Anhydrite, so called from its composition, the anhydrous sulphate of lime, is found in large massive deposits associated with gypsum and rock-salt; it is also known as muriacite and karstenite. It is found crystallised at a few localities, *e.g.* at Aussee in Styria, as brown crystals of cubic habit, A, B, C, in a mixture of clay, rock-salt, and gypsum; in rock-

salt at Stassfurt; and as blue crystals in limestone at Berchtesgaden in Bavaria. Its axial ratios and cleavage are quite different from those of the barytes group, to which it might be expected to belong. The mineral is usually massive, but can even then be recognised by its cleavage. The three cleavage-faces are perpendicular to the axes of the indicatrix, and therefore furnish plates in which the appearance of the interference-figures, as viewed along the acute bisectrix, the obtuse bisectrix, and the third mean line, can be conveniently studied. The B-cleavage is a little less easy than C, and A than B.

GYPSUM.

Gypsum.—Hydrated sulphate of calcium; $CaSO_4 . 2H_2O$; $CaO = 32{\cdot}6$ $SO_3 = 46{\cdot}5$, $H_2O = 20{\cdot}9$.
Monoclinic.

$$a : b : c = 0{\cdot}690 : 1 : 0{\cdot}412. \quad \beta = 80° 42'.$$

$$B = \{010\},\ e = \{\bar{1}03\},\ l = \{111\},\ m = \{110\},\ k = \{130\}.$$

$$Bm\ (010) : (110) = 55° 45',\ ll\ (111) : (1\bar{1}1) = 36° 12',\ mm\ (110) : (1\bar{1}0) = 68° 30',$$
$$Bk\ (010) : (130) = 26° 5'.$$

Twinned on (100), also on (101). Cleavage B, perfect; A {100} and n {$\bar{1}11$}, imperfect. Sectile. Flexible. H = 2; G = 2·3. Colourless. Streak, white. Lustre, vitreous. Transparent; $\gamma = 1{\cdot}530$, $\beta = 1{\cdot}522$. Birefringence, weak, positive; $\gamma - \alpha = 0{\cdot}010$. Axial plane (010). Acute bisectrix inclined at 37° 30′ to the normal of A, and 43° 12′ to the normal of C; $2E = 95°$. Dispersion inclined; $\rho > v$. Fusible (3). Soluble in hydrochloric acid.

With the above description compare crystals from **Bex** (Switzerland).

Gypsum, or selenite (Ital. *gesso*), is a mineral of considerable commercial importance as the source of plaster-of-Paris, which received this name because it was obtained by burning the gypsum from the quarries of Montmartre near Paris; it is also used as a surface dressing for agricultural land. The name is derived from *γύψος*, which may have denoted burnt gypsum. The name selenite is the *selenites* of Dioscorides and Pliny, which also may have been gypsum; this name is now generally used for the crystallised varieties.

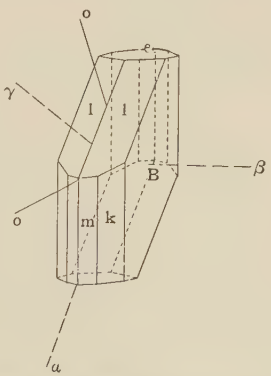


Fig. 726.—Gypsum, B {010}, l {111}, m {110}, k {130}, e {$\bar{1}03$}.

Gypsum occurs in large beds associated with limestones, clays, and marls, and in connection with salt and anhydrite; the best crystals are those which are found in clay (as near Oxford), or lining druses with sulphur (as in Sicily). The crystals are almost always the simple combination B m l, like Fig. 235. At some localities, as at Bex, there is also the face e, which is nearly perpendicular to the prism-edge (Fig. 726), but this face is generally uneven and curved, sometimes concave. Cleavage-flakes parallel to B are flexible, and when bent break along ($\bar{1}01$), which

would be a face at the back of the crystal inclined to the vertical at the angle 66° 10′ ; but this fracture is fibrous and, if examined closely, is seen to consist of the two imperfect cleavages ($\bar{1}11$) ($1\bar{1}1$) at the back of the crystal, corresponding to the faces *l* in front ; the flakes also break unevenly along the imperfect cleavage (100). The (100) cleavage is known as the "conchoidal" cleavage to distinguish it from the ($\bar{1}11$) or "fibrous" cleavage ; the cracks which these cleavages produce on the face B are inclined to one another at 113° 50′. These cracks serve to orientate a cleavage-plate when no crystal faces are present, for the conchoidal cleavage is parallel to the *c*-axis. Other cleavage-cracks can also be produced by pressure.

Cleavage-plates, B, can be obtained as thin as desired, and are useful to produce interference-tints of the different orders ; *e.g.* red of the first order ; such a plate can be used to detect the weak birefringence in sections of minerals which are nearly isotropic, since it becomes elevated in the scale (to blue) or depressed (to yellow) when the plate is superposed on the mineral section ; it may also be used to determine the optical sign (p. 197).

Gypsum is one of those substances whose optical characters vary considerably with change of temperature. At ordinary temperatures the plane of the optic axes is parallel to the plane of symmetry (Fig. 726) and there is strong inclined dispersion. If the interference-figure be viewed through a plate cut perpendicular to the acute bisectrix (such a section is difficult to prepare on account of the cleavage), and the plate be warmed, the angle of the optic axes gradually diminishes, until at 90° C. the crystal is uniaxial for blue light ; a little later it becomes uniaxial for red light ; meanwhile the optic axes for blue begin to open out in a plane perpendicular to the plane of symmetry (as in Fig. 359), and are followed by those for other colours ; above 91° C. the optic axial plane for all colours is perpendicular to (010), and there is slight horizontal dispersion, with $\rho < v$. It is not safe to raise the temperature much further, since at about 110° the mineral begins to give off water and become permanently altered.

During this change the acute bisectrix also changes its position, and moves through about $5\frac{1}{2}$° (between 20° C. and 100° C.) in the plane of symmetry.

In gypsum the conductivity for heat is markedly different in different directions ; and this property can readily be demonstrated as described on p. 121.

Gypsum is also interesting as one of the few minerals in which the change of angles between the faces produced by change of temperature, owing to the different expansion in different directions, can be measured. Mitscherlich studied this by cutting a plate from a twin-crystal at right angles to the twin-plane, and found that on heating such a plate the two halves become inclined to each other by several minutes, owing to the change of angle between the artificial face and the twin-plane.

Twinning on the ortho-pinakoid (100) is very common, the crystals being either juxtaposed, Fig. 234, p. 98, or interpenetrant, Fig. 727 ; the edges of the prism *mm*, which would be truncated by the twin-plane, are parallel in the two individuals. The other law, twin-plane (101), gives

rise to very similar groups, but here the edges *ll*, which would be truncated by the twin-plane, are parallel ; the *m*-faces are easily distinguished from the *l*-faces since their edge is less obtuse.

The twinning on (100) is easily detected, even on cleavage-flakes, by the fact that the fibrous cleavage-cracks do not run uniformly across the crystal, but meet at an angle of 47° 50′ on the line of contact.

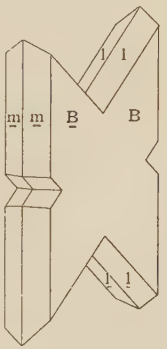


Fig. 727.—Gypsum twinned on (100).

Crystals of gypsum are very apt to be curved or even lenticular (Fig. 445) ; in twins this sometimes produces arrowhead forms. They may also be coloured grey, yellow, brown, or black by impurities. The long crystals from Gotha are sometimes twisted and bent in a fantastic manner.

Massive gypsum, when of a fine grain, is known as alabaster (from ἀλαβαστίτης), and is used for ornamental purposes ; the name is also applied to the white and banded stalagmitic varieties of calcite ("onyx-marble"), and this was probably the material used by the ancients ; this is now known as "oriental alabaster."

Gypsum, whether massive or crystallised, is easily distinguished by its softness from this and other minerals which it resembles ; it is readily scratched by the finger-nail, whereas calcite is not.

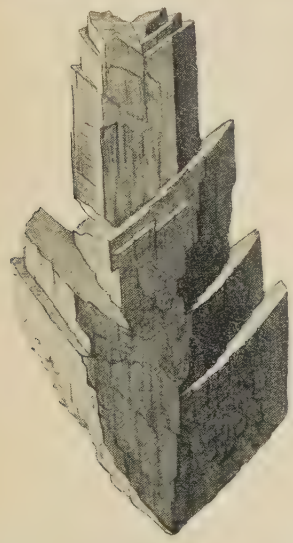


Fig. 728.—Gypsum twinned on (100).

Fibrous gypsum sometimes forms a beautiful material with a satiny lustre or even a pearly opalescence ; it is known by the same name as the fibrous calcite or aragonite, "satin-spar," and is used as an ornamental stone.

Microscopic crystals with the characteristic outline of Fig. 235, and an extinction of $37\frac{1}{2}°$, can be produced by mixing very dilute aqueous solutions of a soluble sulphate and of calcium chloride, or even by the evaporation of sea water, which contains calcium sulphate in solution ; but the more usual form of gypsum obtained by rapid crystallisation in micro-chemical reactions is the tufts of needles shown in Fig. 466.

Some Noteworthy Localities :

Shotover Hill (Oxford).—Large isolated crystals are found in the blue Kimmeridge clay ; these are either simple crystals like Fig. 235, p. 98, or twins like Fig. 234, or Figs. 727 or 728, and are generally more or less opaque owing to cavities containing clay.

Very similar crystals are found in the London clay in the **Isle of Sheppey** and other localities ; here, as elsewhere, they are frequently associated with iron pyrites and marcasite, and have probably been produced

through the decomposition of pyrites in the presence of calcium carbonate (p. 379).

Bex (Switzerland).—Beautiful limpid crystals are here found in the salt mines; they are of the habit of Fig. 726, and generally show the curved and dull plane {$\bar{1}03$}; they are often twinned on (100).

Girgenti (Sicily).—Fine transparent crystals occur with the sulphur and celestite in the marl of this locality; they are usually twins, on (100), and are often curved; the crystals sometimes have the face (100) developed. Here, and at Bex, twin crystals bearing the face ($\bar{1}03$), which is almost exactly perpendicular to the vertical axis, may present an unusual appearance, this form nearly coinciding in the two individuals and constituting a single curved surface. The gypsum of Girgenti and other localities sometimes encloses movable drops of water.

Montmartre (Paris).—The large honey-yellow crystals, found in the beds of gypsum which are interstratified with marls and clays, are almost always lenticular; they are also often twinned on (101), and the curvature of the crystals in these gives rise to the so-called "swallow-tail twins," which are especially conspicuous when bounded by cleavage-faces B. In these twins it will be noticed that the conchoidal cleavage of one individual nearly coincides with the fibrous cleavage of the other.

The selenite of Montmartre is far less flexible and more brittle than that of most localities.

Many other sulphates are found as minerals; of these some are too rare to be considered here, others are soluble in water and are only found as massive or fibrous deposits and incrustations in which the characters of the minerals can scarcely be studied. Among the latter, **chalcanthite** (Fr. *cyanose*), the common blue anorthic sulphate of copper, $CuSO_4 . 5H_2O$, and **melanterite,** the common green ferrous sulphate, $FeSO_4 . 7H_2O$ (monoclinic), are common as decomposition products of copper and iron ores; melanterite in particular is the usual result of the decomposition of marcasite and pyrites, and makes its appearance as a pale green or nearly colourless efflorescence; it may be recognised by its astringent taste.

Epsomite (Germ. *Bittersalz*), $MgSO_4 . 7H_2O$, and **Goslarite,** $ZnSO_4 . 7H_2O$, are not isomorphous with melanterite, but belong to the sulphur class of the orthorhombic system; artificial mixtures show that they belong to an isodimorphous series. Like chalcanthite and melanterite, these minerals are often abundant in mine waters, and form botryoidal crusts and fibrous efflorescences.

Among the **alums,** $R'Al(SO_4)_2 . 12H_2O$, potash- and ammonia-alums occur in Nature; but these also are merely fibrous deposits in shales and clays.

Alunite, or alumstone, $K(AlO_2H_2)_3(SO_4)_2$, is a very different mineral, insoluble in water and possessing a hardness of 4. It is found in white, impure, massive deposits in volcanic rocks which have been

permeated by sulphurous vapours. In the neighbourhood of Rome and in Hungary it is burnt for the manufacture of alum; crystals are rare, but small rhombohedra may sometimes be observed in cavities.

The following double salts also occur:

Glauberite, $Na_2SO_4 . CaSO_4$, found in well-developed monoclinic crystals at Stassfurt and in other salt mines.

Hanksite, $9Na_2SO_4 . 2Na_2CO_3 . KCl$, found in large hexagonal prisms and pyramids in the borax deposits of California.

There are also a number of basic sulphates, mostly hydrated, of copper and of iron.

THE CHROMATES

The chromates as a group are isomorphous with the sulphates, but very few of them occur as minerals. A calcium chromate isomorphous with gypsum has been produced artificially, while artificial $BaCrO_4$ is isomorphous with barytes. The only chromate of any importance among minerals is **crocoite** (Germ. *Rothbleierz*), the lead chromate $PbCrO_4$, which is found in fine monoclinic crystals, but is not isomorphous with any known mineral sulphate. Crocoite is of a beautiful hyacinth-red (which loses its brilliancy on exposure to light), and adamantine lustre, with orange-yellow streak. Crystals of acute habit are found in quartz veins in the granite of Beresov in the Urals, and in Brazil. Long transparent prisms with oblique terminations have recently been found near Dundas in Tasmania.

Crocoite has been used as a paint and possesses the same composition as the artificial chrome-yellow, which has the colour of the crocoite streak. It was in this mineral that the element chromium was discovered by Vauquelin.

SECTION XXVII

THE TUNGSTATES, NIOBATES, AND NITRATES

Of the remaining classes of minerals only a few species deserve brief mention, since most of them are either (tungstates and niobates) very rare, or (nitrates) soluble compounds which occur only in beds of massive material.

The Tungstates

THE SCHEELITE GROUP

Scheelite	$CaWO_4$
Wulfenite	$PbMoO_4$
Stolzite	$PbWO_4$
Cuprotungstite	$CuWO_4$
Powellite	$CaMoO_4$

Scheelite.—Tungstate of calcium; $CaWO_4$; CaO 19·5, WO_3 80·5. Tetragonal; symmetry, tetragonal equatorial. $a:c=1:1·536$. Common form, bipyramids. Supplementary twinning. Cleavage {111}, fair; {101}, imperfect. Brittle. Fracture, uneven. H = 4½; G = 6. White. Streak, white. Lustre, vitreous to adamantine. Translucent; $\omega = 1·919$. Birefringence rather weak, positive; $\epsilon - \omega = 0·016$. Fusible with difficulty (5). Decomposed by hydrochloric acid.

With the above description compare crystals from **Zinnwald** (Bohemia).

Wulfenite.—Molybdate of lead; $PbMoO_4$; PbO = 60·8, MoO_3 = 39·2. Tetragonal; symmetry, tetragonal polar. $a:c=1:1·577$. Common form, square tables. Cleavage {111}, fair. Brittle. Fracture, sub-conchoidal. H = 3; G = 6·7. Red. Streak, white. Lustre, adamantine to resinous. Translucent; $\omega = 2·402$. Birefringence, strong, negative; $\epsilon - \omega = -0·098$. Easily fusible (2). Decomposed by hydrochloric acid.

With the above description compare crystals from **Yuma County** (Arizona).

Scheelite generally occurs in square bipyramids {101} somewhat resembling octahedra (Fig. 137, p. 60), and the tetragonal (as opposed to di-tetragonal) character of the symmetry is shown by the triangular faces which occur on only one corner of each octahedron-face, or by striations corresponding to these. Supplementary twins may easily be mistaken

for simple crystals unless attention be paid to these striations, which in the twin meet at an angle on each octahedron face.

Scheelite is one of the minerals found associated with topaz, fluor, apatite, etc., in connection with the tin-bearing veins of certain granites.

Crystals of considerable size have been found under these conditions in the Bohemian and Saxon tin-mining region; also associated with molybdenite, apatite, gilbertite and lead ores at Carrock Fell, Cumberland, and in chlorite with wolframite at Tavistock in Devonshire.

Tungstic acid was discovered in this mineral by the Swedish chemist, Scheele, after whom it is named; the mineral had previously been called *tungsten* ("heavy stone") and regarded as an iron ore.

Wulfenite (Germ. *Gelbbleierz*) is found in brilliant red crystals, square plates with bevelled edges and very flat pyramid faces, in Arizona, and in thin pale yellow square plates in the lead mines of Carinthia. The tetragonal nature of the symmetry may sometimes be detected by the presence of pyramid faces like those of scheelite, but sometimes also by the faces of a prism {*hk*0}, which is tetragonal and not di-tetragonal (as shown in Fig. 729).

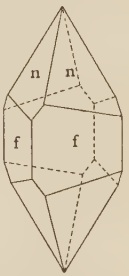


Fig. 729.—Wulfenite, *n* {111}, *f* {320}.

Crystals have recently been described, from New Mexico, which are pyramids somewhat resembling Fig. 729, with the exception that they are differently terminated at the two ends. The symmetry is well shown by the crystals from Saxony figured on p. 61 (Fig. 140). This mineral is then certainly polar, but there is no evidence of such a polarity in scheelite, nor in stolzite, which is found in yellow bipyramids.

The minerals of this group enter into isomorphous mixture with each other to a small extent; scheelite contains some molybdate, wulfenite some lime. Cuprotungstite and powellite are very rare minerals.

WOLFRAMITE

Wolframite.—Tungstate of manganese and iron; $(Fe, Mn)WO_4$; FeO – 19 to 2, MnO = 6 to 22, $WO_3 = 76$. Monoclinic; holosymmetric. Cleavage {010}, perfect; {100}, imperfect. Brittle. Fracture, uneven. H = 5½; G = 7·3. Black. Streak, dark reddish-brown. Lustre, sub-metallic. Opaque. Fusible (3) to a magnetic bead. Decomposed by hydrochloric acid.

With the above description compare crystals from **Schlaggenwald** (Bohemia)

Wolframite occurs generally in tin-bearing regions under the same conditions as scheelite, and is often associated with that mineral; it is fairly common as a black mineral accompanying cassiterite in Cornwall and elsewhere, and is commercially of importance as a source of tungsten for use in the manufacture of tungsten steel and of electric lamp filaments.

It may generally be recognised by its lustre and the single perfect cleavage. It approximates very closely in its angles to orthorhombic symmetry, and was long supposed to belong to that system; it is, however, sometimes twinned on (100), and also on (023).

Wolframite bears no crystallographic relation to the scheelite group.

An almost pure tungstate of manganese, containing only a small percentage of iron, is a mineral known as **hübnerite,** which has a form like that of wolframite.

The tungstic acid of scheelite, stolzite, and wolframite is best detected by the yellow residue of tungstic oxide left after boiling with aqua regia ; the blowpipe reactions are masked by the presence of iron and manganese, especially in the case of wolframite. The molybdic acid of wulfenite may be detected by the permanent intense blue colour given by adding metallic zinc, after moistening with water the residue obtained by treatment with hydrochloric acid and evaporation ; the similar coloration obtained from wolframite fades on dilution.

The Niobates and Tantalates

These are a rare group of minerals, of which many are found in the granitic rocks of Sweden ; they are chiefly of chemical interest as the sources of rare elements such as yttrium, erbium, cerium, thorium, lanthanum, and didymium ; they are mostly black opaque minerals, imperfectly crystallised and difficult to distinguish.

The best crystallised and most widely distributed of the series is **columbite,** a niobate of iron and manganese $(Fe, Mn)Nb_2O_6$, in which a variable proportion of niobic is replaced by tantalic acid. This occurs in lustrous black opaque crystals of submetallic lustre belonging to the orthorhombic system. The specific gravity of all these minerals is high ; that of columbite is about 5·3, rising to 7·3 with increase of TaO_3.

It was in columbite that the element niobium was first discovered.

Brilliant crystals of columbite are found in the cryolite of West Greenland ; and among localities already mentioned for other minerals may be added Bodenmais in Bavaria, where columbite occurs in the granite with magnetite and cordierite, and the granite of the Ilmen Mountains in Siberia.

The Nitrates

These are of immense commercial importance as fertilisers and as a source of nitric acid. Being soluble in water they are found almost exclusively as massive or fibrous deposits or as incrustations. The only two nitrates of importance are :

Nitre (saltpetre, salitre, Germ. *Kalisalpeter*), KNO_3.

Nitratine (Chili saltpetre, caliche, Germ. *Natronsalpeter*), $NaNO_3$.

Nitre is found in India as a white surface-deposit, and in many parts of the world as an efflorescence or crystalline crust mixed with porous soils.

Nitratine occurs in large deposits in the dry districts of Chili, associated with gypsum and salt ; the " caliche," or impure nitrate, is sometimes of a vivid yellow owing to the presence of iodine.

Both nitre and nitratine are probably to a large extent of organic

origin, being formed by the action of nitrifying bacteria in the soil on nitrogenous organic matter.

The crystallographic relationship between sodium nitrate and calcium carbonate has been pointed out on p. 266; crystals of the former are almost unknown in Nature.

TABLES

General Survey of the Mineral Kingdom

The following list contains the most important and best known minerals, together with many which, though very rare, are inserted because they represent important classes or groups.

The minerals are divided into classes according to the non-metallic elements, or the acid radicals, which they contain (*cf.* p. 228).

Within each class the minerals are arranged as follows :

1. Compounds of monovalent elements . . . R′-compounds
2. „ „ divalent elements (sometimes with monovalent) . . . . . R″-compounds
3. Compounds of trivalent elements (sometimes with monovalent or divalent) . . . . . R‴-compounds
4. Miscellaneous (including double salts containing more than one acid radical, and other minerals of uncertain affinities).

A mineral group is placed in the division to which its simplest members may be referred, but it must be remembered that within a group one or more atoms may be replaced not only by atoms of vicarious elements but sometimes by other atoms having different valencies, provided that the total valency is the same. Thus the pyroxene group is $R''SiO_3$ if its simplest members, such as enstatite, $MgSiO_3$, or diopside $CaMg(SiO_3)_2$, be taken as the type ; hence it is placed in the second of the above divisions. But the group also contains members of the type $R'R'''(SiO_3)_2$, such as spodumene, $LiAl(SiO_3)_2$; these, if considered by themselves, should belong to division 3; but they cannot be separated from the pyroxene group, and the group, as a whole, is classed by its simplest type.

Again, within each group the formulæ quoted are the simplest possible, but it must be remembered that the analyses seldom represent so simple a composition, since any of the vicarious replacements mentioned on p. 245 (such as OH for F, Fe″ for Mg″, Fe‴ for Al‴, etc.) may take place. Further, there may be isomorphous mixtures between the different members of a group ; where these are sufficiently well defined to receive special names they are incorporated in the group. It must be remembered also that in the silicates Al may often belong partly to the basic and partly to the acid radical, H to the basic radical (as hydroxyl), or to water of crystallisation, as well as to an acid salt ; these are difficulties which make it impossible in the present state of our knowledge to draw up a satisfactory classification of minerals.

List of the Principal Minerals

Class I.—Elements

Metals—

The Gold Group	Copper . .	Cu
	Silver . .	Ag
	Gold . .	Au
	Mercury . .	Hg

Metals (*continued*)—		
	Amalgam	(Ag,Hg)
	Lead	Pb
The Platinum Group	Iron	Fe
	Awaruite	(Ni,Fe)
	Platinum	Pt
	Palladium	Pd
	Iridosmine	(Ir,Os)
The Arsenic Group	Arsenic	As
	Allemontite	(Sb,As)
	Antimony	Sb
	Bismuth	Bi
Non-metals—		
	Sulphur	S
	Diamond	C
	Graphite	C

Class II.—Haloids

R′-haloids—		
The Salt Group	Salt	NaCl
	Sylvite	KCl
	Sal-ammoniac	NH_4Cl
	Villiaumite	NaF
	Cerargyrite	AgCl
	Bromargyrite	AgBr
	Embolite	Ag(Cl,Br)
	Iodembolite	Ag(Cl,Br,I)
	Nantockite	CuCl
	Marshite	CuI
	Miersite	4AgI.CuI
	Iodyrite	AgI
	Calomel	HgCl
R″-haloids—		
	Fluor	CaF_2
	Sellaite	MgF_2
	Cotunnite	$PbCl_2$
	Bischofite	$MgCl_2.6H_2O$
	Chlormanganokalite	$4KCl.MnCl_2$
	Rinneite	$3KCl.NaCl.FeCl_2$
	Carnallite	$KCl.MgCl_2.6H_2O$
R‴-haloids—		
	Tysonite	$(Ce,La,Di)F_3$
	Fluellite	$AlF_3.H_2O$
	Cryolite	$3NaF.AlF_3$
	Chiolite	$5NaF.3AlF_3$
	Cryolithionite	$3NaF.3LiF.2AlF_3$
	Erythrosiderite	$2KCl.FeCl_3.H_2O$
	Pachnolite / Thomsenolite	$NaF.CaF_2.AlF_3.H_2O$
	Ralstonite	$2NaF.MgF_2.6Al(F,OH)_3.4H_2O$
	Prosopite	$CaF_2.2Al(F,OH)_3$
	Yttrofluorite	$CaF_2.xYF_3$
	Yttrocerite	$CaF_2.x(Ce,Y)F_3$
Oxychlorides, etc.—		
	Laurionite / Paralaurionite	Pb(OH)Cl

Oxychlorides, etc. (*continued*)—

	Fiedlerite	$2Pb(OH)Cl.PbCl_2$
	Percylite	$Pb(OH)Cl.Cu(OH)Cl$
	Cumengeite	$4Pb(OH)Cl.4Cu(OH)Cl.H_2O$
	Pseudoboleite	$4Pb(OH)Cl.4Cu(OH)Cl.PbCl_2.2H_2O$
	Boleite	$8Pb(OH)Cl.8Cu(OH)Cl.PbCl_2.3AgCl.H_2O$
	Atacamite, Paratacamite	$Cu(OH)Cl.Cu(OH)_2$
	Penfieldite	$2PbCl_2.PbO$
	Matlockite	$PbCl_2.PbO$
	Mendipite	$PbCl_2.2PbO$
	Schwartzembergite	$Pb(I,Cl)_2.2PbO$

CLASS III.—SULPHIDES, ARSENIDES, ETC.

R′-sulphides—

The Copper-glance Group	Acanthite	Ag_2S
	Stromeyerite	$(Cu,Ag)_2S$
	Copper-glance	Cu_2S
The Argentite Group	Argentite	Ag_2S
	Naumannite	Ag_2Se
	Hessite	Ag_2Te
	Petzite	$(Ag,Au)_2Te$

R′′-sulphides—

The Galena Group	Galena	PbS
	Clausthalite	$PbSe$
	Altaite	$PbTe$
The Blende Group	Blende	ZnS
	Alabandite	MnS
	Pentlandite	$(Fe,Ni)S$
The Millerite Group	Wurtzite	ZnS
	Greenockite	CdS
	Millerite	NiS
	Niccolite	$NiAs$
	Breithauptite	$NiSb$
	Pyrrhotite	FeS
	Cinnabar	HgS
	Covellite	CuS
	Metacinnabarite	HgS
	Tiemannite	$HgSe$
	Coloradoite	$HgTe$
The Pyrites Group	Pyrites	FeS_2
	Hauerite	MnS_2
	Smaltite	$CoAs_2$
	Chloanthite	$NiAs_2$
	Cobaltite	$CoAsS$
	Gersdorffite	$NiAsS$
	Ullmannite	$NiSbS$
	Sperrylite	$PtAs_2$
	Laurite	RuS_2
The Marcasite Group	Marcasite	FeS_2
	Löllingite	$FeAs_2$
	Mispickel	$FeAsS$
	Glaucodote	$(Co,Fe)AsS$
	Safflorite	$CoAs_2$
	Rammelsbergite	$NiAs_2$

R‴-sulphides—

	Realgar	AsS
The Stibnite Group	Orpiment	As_2S_3
	Stibnite	Sb_2S_3
	Bismuthite	Bi_2S_3
	Guanajuatite	Bi_2Se_3
	Tetradymite	$Bi_2(Te,S)_3$

Miscellaneous Sulphides, etc.—

Whitneyite	Cu_9As
Algodonite	Cu_6As
Domeykite	Cu_3As
Dyscrasite	Ag_3Sb
Skutterudite	$CoAs_3$
Molybdenite	MoS_2
Muthmannite	$(Au,Ag)Te$
Krennerite / Sylvanite	$(Au,Ag)Te_2$
Calaverite	$AuTe_2$
Nagyagite	$(Pb,Au)_{16}Sb_3(S,Te)_{24}$

Class IV.—Sulpho-salts

Sulphoferrites, etc.—

Erubescite	$3Cu_2S.Fe_2S_3$
Chalcopyrite	$Cu_2S.Fe_2S_3$
Cubanite	$CuS.Fe_2S_3$
Carrollite	$CuS.Co_2S_3$
Linnæite	$CoS.Co_2S_3$
Polydymite	$2NiS.Ni_2S_3$
Sternbergite	$Ag_2S.Fe_4S_5$

Sulphostannates and Sulphogermanates—

Argyrodite	$4Ag_2S.GeS_2$
Canfieldite	$4Ag_2S.(Sn,Ge)S_2$
Stannite	$Cu_2S.FeS.SnS_2$
Cylindrite	$6PbS.6SnS_2.Sb_2S_3$
Franckeite	$5PbS.2SnS_2.Sb_2S_3$

Sulpharsenites, Sulphantimonites, and Sulphobismuthites—

The Polybasite Group	Pearceite	$9Ag_2S.As_2S_3$
	Polybasite	$9Ag_2S.Sb_2S_3$
The Stephanite Group	Stephanite	$5Ag_2S.Sb_2S_3$
	Geocronite	$5PbS.Sb_2S_3$
The Meneghinite Group	Jordanite	$4PbS.As_2S_3$
	Meneghinite	$4PbS.Sb_2S_3$
The Tetrahedrite Group	Tennantite	$3Cu_2S.As_2S_3$
	Tetrahedrite	$3Cu_2S.Sb_2S_3$
	Lengenbachite	$6PbS.(Ag,Cu)_2S.2As_2S_3$
The Pyrargyrite Group	Proustite	$3Ag_2S.As_2S_3$
	Pyrargyrite	$3Ag_2S.Sb_2S_3$
The Pyrostilpnite Group	Xanthoconite	$3Ag_2S.As_2S_3$
	Pyrostilpnite	$3Ag_2S.Sb_2S_3$
The Bournonite Group	Seligmannite	$2PbS.Cu_2S.As_2S_3$
	Bournonite	$2PbS.Cu_2S.Sb_2S_3$
	Aikinite	$2PbS.Cu_2S.Bi_2S_3$
	Boulangerite	$5PbS.2Sb_2S_3$

Sulpharsenites, etc. (*continued*)—		
	Freieslebenite, Diaphorite	$5(Ag_2,Pb)S.2Sb_2S_3$
	Dufrenoysite	$2PbS.As_2S_3$
	Plumosite	$2PbS.Sb_2S_3$
	Jamesonite	$5(Pb,Fe)S.3Sb_2S_3$
	Rathite	$3PbS.2As_2S_3$
	Baumhauerite	$4PbS.3As_2S_3$
The Plagionite Group	Liveingite	$5PbS.4As_2S_3$
	Plagionite	$5PbS.4Sb_2S_3$
The Wolfsbergite Group	Wolfsbergite	$Cu_2S.Sb_2S_3$
	Emplectite	$Cu_2S.Bi_2S_3$
	Scleroclase	$PbS.As_2S_3$
	Zinckenite	$PbS.Sb_2S_3$
	Hutchinsonite	$PbS.(Tl,Ag)_2S.2As_2S_3$
	Andorite	$2PbS.Ag_2S.3Sb_2S_3$
	Smithite	$Ag_2S.As_2S_3$
	Miargyrite	$Ag_2S.Sb_2S_3$
	Lorandite	$Tl_2S.As_2S_3$
	Berthierite	$FeS.Sb_2S_3$
	Vrbaite	$Tl_2S.2As_2S_3.Sb_2S_3$
Sulpharsenates, etc.—		
	Sulvanite	$3Cu_2S.V_2S_5$
	Enargite	$3Cu_2S.As_2S_5$
	Famatinite	$3Cu_2S.Sb_2S_5$
Oxysulphides—		
	Kermesite	Sb_2S_2O

Class V.—Oxides

R′-oxides—		
	Ice	H_2O
	Cuprite	Cu_2O
R″-oxides—		
	Periclase	MgO
	Zincite	ZnO
	Melaconite	CuO
	Massicot	PbO
	Montroydite	HgO
The Brucite Group	Brucite	$Mg(OH)_2$
	Pyrochroite	$Mn(OH)_2$
R‴-oxides—		
The Corundum Group	Corundum	Al_2O_3
	Hæmatite	Fe_2O_3
The Senarmontite Group	Arsenolite	As_2O_3
	Senarmontite	Sb_2O_3
The Valentinite Group	Claudetite	As_2O_3
	Valentinite	Sb_2O_3
The Göthite Group	Diaspore	$AlO(OH)$
	Manganite	$MnO(OH)$
	Göthite	$FeO(OH)$
	Lepidocrocite	$FeO(OH)$
	Sassolite	$B(OH)_3$
	Hydrargillite	$Al(OH)_3$
	Bauxite	$Al_2O_3+xH_2O$
	Limonite	$Fe_2O_3+xH_2O$

R''''-oxides—

	Tellurite	TeO_2
The Cassiterite Group	Cassiterite	SnO_2
	Polianite	MnO_2
	Rutile	TiO_2
	Plattnerite	PbO_2
	Anatase	TiO_2
	Brookite	TiO_2
	Pyrolusite	MnO_2
	Psilomelane	$MnO_2 + xH_2O + yMnO + zBaO$
	Baddeleyite	ZrO_2
	Thorianite	$(Th,U)O_2$
	Quartz	SiO_2
	Tridymite	SiO_2
	Cristobalite	SiO_2
	Chalcedony	SiO_2
	Opal	$SiO_2 + xH_2O$
	Melanophlogite	$SiO_2 + xH_2O + ySO_3$

Class VI.—Aluminates, Ferrites, etc.

The Spinel Group	Spinel	$MgAl_2O_4$
	Hercynite	$FeAl_2O_4$
	Gahnite	$ZnAl_2O_4$
	Jacobsite	$(Mn,Mg)(Fe,Mn)_2O_4$
	Franklinite	$(Fe,Zn,Mn)(Fe,Mn)_2O_4$
	Magnetite	$FeFe_2O_4$
	Magnesioferrite	$MgFe_2O_4$
	Chromite	$FeCr_2O_4$
	Chrysoberyl	$BeAl_2O_4$

Class VII.—Borates

R'-borates—

	Borax	$Na_2B_4O_7.10H_2O$
	Larderellite	$(NH_4)_2B_8O_{13}.4H_2O$

R''-borates—

	Hambergite	$Be(BeOH)BO_3$
	Sussexite	$H(Mn,Mg,Zn)BO_3$
	Pinnoite	$Mg(BO_2)_2.3H_2O$
	Colemanite	$Ca_2B_6O_{11}.5H_2O$
	Meyerhofferite	$Ca_2B_6O_{11}.7H_2O$
	Inyoite	$Ca_2B_6O_{11}.13H_2O$
	Ulexite	$NaCaB_5O_9.8H_2O$
	Heintzite	$KMg_2B_{11}O_{19}.9H_2O$

R'''-borates—

	Jeremejevite	$AlBO_3$
	Rhodizite	$KAl_2B_3O_8$

Miscellaneous borates—

	Nordenskiöldine	$CaSn(BO_3)_2$
	Ludwigite	$Mg_2O(BO_2)(Fe'''O_2)$
	Pinakiolite	$(Mg,Mn)_2O(BO_2)(Mn'''O_2)$
	Boracite	$Mg_7Cl_2B_{16}O_{30}$
	Sulphoborite	$4HMgBO_3.2MgSO_4.7H_2O$

Class VIII.—Manganites, etc.

Braunite	$Mn''Mn''''O_3$
Bixbyite	$Fe''Mn''''O_3$
Hausmannite	$Mn''_2Mn''''O_4$
Chalcophanite	$(Mn,Zn)Mn''''_2O_5.2H_2O$
Minium	$Pb''_2Pb''''O_4$

Class IX.—Carbonates

R′-carbonates—

Teschemacherite	$H(NH_4)CO_3$
Trona	$HNa_3(CO_3)_2.2H_2O$
Thermonatrite	$Na_2CO_3.H_2O$
Natron	$Na_2CO_3.10H_2O$

R″-carbonates—

The Calcite Group	Calcite	$CaCO_3$
	Dolomite	$CaCO_3.MgCO_3$
	Magnesite	$MgCO_3$
	Ankerite	$Ca(Mg,Fe)(CO_3)_2$
	Chalybite	$FeCO_3$
	Rhodochrosite	$MnCO_3$
	Sphærocobaltite	$CoCO_3$
	Calamine	$ZnCO_3$
The Aragonite Group	Aragonite	$CaCO_3$
	Alstonite	$(Ca,Ba)CO_3$
	Witherite	$BaCO_3$
	Strontianite	$SrCO_3$
	Cerussite	$PbCO_3$
	Barytocalcite	$CaCO_3.BaCO_3$
	Malachite	$(CuOH)_2CO_3$
	Chessylite	$Cu(CuOH)_2(CO_3)_2$
	Nesquehonite	$MgCO_3.3H_2O$
	Hydromagnesite	$Mg_2(MgOH)_2(CO_3)_3.3H_2O$
	Pirssonite	$Na_2CO_3.CaCO_3.2H_2O$
	Gaylussite	$Na_2CO_3.CaCO_3.5H_2O$

R‴-carbonates—

Lanthanite	$La_2(CO_3)_3.9H_2O$
Dawsonite	$Na(AlO_2H_2)CO_3$

Miscellaneous carbonates—

	Bastnäsite	$(Ce,La,Di)FCO_3$
The Parisite Group	Parisite	$Ca(CeF)_2(CO_3)_3$
	Cordylite	$Ba(CeF)_2(CO_3)_3$
	Phosgenite	$(PbCl)_2CO_3$
	Northupite	$Na_2CO_3.MgCO_3.NaCl$

Class X.—Silicates and Titanates

R″-silicates—

The Olivine Group	Monticellite	$CaMgSiO_4$
	Glaucochroite	$CaMnSiO_4$
	Forsterite	Mg_2SiO_4
	Olivine	$(Mg,Fe)_2SiO_4$
	Fayalite	Fe_2SiO_4
	Knebelite	$(Fe,Mn)_2SiO_4$
	Roepperite	$(Fe,Mn,Zn)_2SiO_4$
	Tephroite	Mn_2SiO_4
	Trimerite	$MnBeSiO_4$

R″-silicates (*continued*)—

The Phenacite Group	Phenacite	Be_2SiO_4
	Willemite	Zn_2SiO_4
	Dioptase	H_2CuSiO_4
	Bementite	$H_6Mn_5(SiO_4)_4$
The Chondrodite Group	Chondrodite	$Mg_3(MgF)_2(SiO_4)_2$
	Humite	$Mg_5(MgF)_2(SiO_4)_3$
	Clinohumite	$Mg_7(MgF)_2(SiO_4)_4$
	Leucophœnicite	$Mn_5(MnOH)_2(SiO_4)_3$
	Hodgkinsonite	$Mn(ZnOH)_2SiO_4$
The Pyroxene Group	Enstatite	$MgSiO_3$
	Hypersthene	$(Mg,Fe)SiO_3$
	Diopside	$CaMg(SiO_3)_2$
	Hedenbergite	$CaFe(SiO_3)_2$
	Schefferite	$(Ca,Mn)(Mg,Fe)(SiO_3)_2$
	Jeffersonite	$(Ca,Mn)(Mg,Fe,Zn)(SiO_3)_2$
	Augite	$Ca(Mg,Fe)Si_2O_6$ / $(Ca,Mg,Fe)(Al,Fe)_2SiO_6$
	Acmite	$NaFe'''(SiO_3)_2$
	Spodumene	$LiAl(SiO_3)_2$
	Jadeite	$NaAl(SiO_3)_2$
	Rhodonite	$MnSiO_3$
	Babingtonite	$(Ca,Fe,Mn)SiO_3$ / $Fe_2(SiO_3)_3$
	Wollastonite	$CaSiO_3$
	Alamosite	$PbSiO_3$
	Pectolite	$HNaCa_2(SiO_3)_3$
	Schizolite	$HNa(Ca,Mn)_2(SiO_3)_3$
The Amphibole Group	Anthophyllite	$MgSiO_3$
	Tremolite	$CaMg_3(SiO_3)_4$
	Actinolite	$Ca(Mg,Fe)_3(SiO_3)_4$
	Hornblende	$Ca(Mg,Fe)_3Si_4O_{12}$ / $CaMg_2(Al,Fe)_2Si_3O_{12}$ / $NaAl(SiO_3)_2$
	Glaucophane	$NaAl(SiO_3)_2$ / $MgSiO_3$
	Riebeckite	$NaFe'''(SiO_3)_2$ / $FeSiO_3$
	Ænigmatite	$(Fe'',Na_2)(Si,Ti)O_3$ / $Na(Al,Fe''')(SiO_3)_2$
The Ilmenite Group	Ilmenite	$FeTiO_3$
	Geikielite	$MgTiO_3$
	Pyrophanite	$MnTiO_3$
	Perovskite	$CaTiO_3$
	Hemimorphite	$(ZnOH)_2SiO_3$
	Clinohedrite	$(ZnOH)(CaOH)SiO_3$
	Hillebrandite	$(CaOH)_2SiO_3$
	Cuspidine	$(CaF)_2SiO_3$
	Leucophane	$NaCaBeF(SiO_3)_2$
	Talc	$H_2Mg_3(SiO_3)_4$
	Serpentine	$H_4Mg_3Si_2O_9$
	Titanite	$CaTiSiO_5$
	Keilhauite	$CaTiSiO_5$ / $(Al,Fe,Y)_2SiO_5$

R″-silicates (*continued*)—

	Barysilite	$Pb_3Si_2O_7$
	Hardystonite	$Ca_2ZnSi_2O_7$
	Bertrandite	$Be_2(BeOH)_2Si_2O_7$
	Ganomalite	$Ca_4Pb_4(PbOH)_2(Si_2O_7)_3$
	Nasonite	$Ca_4Pb_4(PbCl)_2(Si_2O_7)_3$
	Eudidymite / Epididymite	$HNaBeSi_3O_8$
	Benitoite	$BaSi_3TiO_9$
	Lorenzenite	$Na_2Si_2Ti_2O_9$
	Neptunite	$(Na,K)_2(Fe'',Mn'')Si_4TiO_{12}$
	Astrophyllite	$(Na,K)_4(Fe'',Mn'')_4Si_4TiO_{16}$
	Inesite	$2(Mn,Ca)SiO_3.[H_2O]$
	Okenite	$H_2Ca(SiO_3)_2.[H_2O]$
	Apophyllite	$(H,K)_2Ca(SiO_3)_2.[H_2O]$
	Gyrolite	$Ca_2Si_3O_8.[H_2O]$
	Deweylite	$Mg_4Si_3O_{10}+xH_2O$
	Chrysocolla	$CuSiO_3+xH_2O$

R‴-silicates—

	Eulytite / Agricolite	$Bi_4(SiO_4)_3$
	Pseudobrookite	$Fe'''_4(TiO_4)_3$
	Topaz	$(AlF)_2SiO_4$
	Andalusite	$Al(AlO)SiO_4$
	Cyanite	$(AlO)_2SiO_3$
	Sillimanite	Al_2SiO_5
	Pyrophyllite	$H_2Al_2(SiO_3)_4$
	Kaolinite	$H_4Al_2Si_2O_9$
	Allophane	$Al_2SiO_5+xH_2O$
	Dumortierite	$Al(AlO)_7(BOH)(SiO_4)_3$
	Zunyite	$Al_2(AlO_2H_2)_6(SiO_4)_3$
	Eucryptite	$LiAlSiO_4$
	Kaliophilite	$KAlSiO_4$
	Nepheline	$NaAlSiO_4$
	Cancrinite	$H_6Na_6CaAl_3(CO_3Na)_2(SiO_4)_9$
	Arizonite	$Fe'''_2(TiO_3)_3$
	Leucite	$KAl(SiO_3)_2$
	Pollucite	$H_2Cs_4Al_4(SiO_3)_9$
	Ussingite	$HNa_2Al(SiO_3)_3$
	Petalite	$LiAl(Si_2O_5)_2$
	Thalenite	$Y_2Si_2O_7$
	Thortveitite	$(Sc,Y)_2Si_2O_7$
The Sodalite Group	Sodalite	$Na_4(AlCl)Al_2(SiO_4)_3$
	Hackmanite	$Na_4(AlCl)Al_2(SiO_4)_3$ / $Na_4(AlSNa)Al_2(SiO_4)_3$
	Lazurite	$Na_4(AlS_3Na)Al_2(SiO_4)_3$
	Nosean	$Na_4(AlSO_4Na)Al_2(SiO_4)_3$
	Haüyne	$Na_2Ca(AlSO_4Na)Al_2\,SiO_4)_3$
The Felspar Group	Orthoclase	$KAlSi_3O_8$
	Hyalophane	$KAlSi_3O_8$ / $BaAl_2Si_2O_8$
	Celsian	$BaAl_2Si_2O_8$
	Anorthoclase	$(Na,K)AlSi_2O_8$
	Microcline	$KAlSi_3O_8$

R‴-silicates (*continued*)—

The Felspar Group (*continued*)—	Albite	$NaAlSi_3O_8$ . . . Ab
	Oligoclase	Ab_6An to Ab_3An
	Andesine	Ab_3An to AbAn
	Labradorite	AbAn to $AbAn_3$
	Bytownite	$AbAn_3$ to $AbAn_6$
	Anorthite	$CaAl_2Si_2O_8$ . . . An
The Mica Group	Muscovite	$H_2KAl_3(SiO_4)_3$
	Paragonite	$H_2NaAl_3(SiO_4)_3$
	Phlogopite	$(K,H,MgF)_3Mg_3Al(SiO_4)_3$
	Biotite	$(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$
	Zinnwaldite	$(K,Li)_3Fe(AlF_2)Al_2(Si_3O_8)(SiO_4)_2$
	Lepidolite	$K_4Li_4H(AlF_2)_3Al_4(Si_3O_8)_3(SiO_4)_3$
The Scapolite Group	Marialite	$Na_4Al_2(AlCl)(Si_3O_8)_3$
	Scapolite	$Na_4Al_2(AlCl)(Si_3O_8)_3$ $Ca_4Al_5(AlO)(Si_2O_8)_3$
	Meionite	$Ca_4Al_5(AlO)(Si_2O_8)_3$
The Melilite Group	Sarcolite	$(Ca,Na_2)_3Al_2(SiO_4)_3$
	Gehlenite	$Ca_3(AlO)_2(SiO_4)_2$
	Melilite	$Ca_3(AlO)_2(SiO_4)_2$ $Ca_2MgSi_2O_7$
The Zeolites	Analcite	$NaAl(SiO_3)_2.[H_2O]$
	Thomsonite	$2(Na_2,Ca)Al_2(SiO_4)_2.[5H_2O]$
The Natrolite Group	Natrolite	$Na_2Al(AlO)(SiO_3)_3.[2H_2O]$
	Mesolite	$Na_2Al(AlO)(SiO_3)_3.[2H_2O]$ $CaAl(AlO_2H_2)(SiO_3)_3.[2H_2O]$
	Scolecite	$CaAl(AlO_2H_2)(SiO_3)_3.[2H_2O]$
The Heulandite Group	Edingtonite	$BaAl(AlO_2H_2)(SiO_3)_3.[2H_2O]$
	Heulandite	$Ca(AlSi_3O_8)_2.[5H_2O]$
	Brewsterite	$(Ba,Sr)(AlSi_3O_8)_2.[5H_2O]$
The Stilbite Group	Stilbite	$(Ca,Na_2)(AlSi_3O_8)_2.[6H_2O]$
	Phillipsite	$(Ca,K_2,Na_2)(AlSi_3O_8)_2.[6H_2O]$ $(Ca,K_2,Na_2)(Al_2Si_2O_8).[3H_2O]$
	Wellsite	$(Ca,Ba,K_2)(AlSi_3O_8)_2.[6H_2O]$ $(Ca,Ba,K_2)(Al_2Si_2O_8).[3H_2O]$
	Harmotome	$(Ba,K_2)(AlSi_3O_8)_2.[6H_2O]$ $(Ba,K_2)(Al_2Si_2O_8).[3H_2O]$
The Chabazite Group	Chabazite	$(Ca,Na_2)(AlSi_3O_8)_2.[8H_2O]$ $(Ca,Na_2)(Al_2Si_2O_8).[8H_2O]$
	Gmelinite	$(Na_2,Ca)(AlSi_3O_8)_2.[8H_2O]$ $(Na_2,Ca)(Al_2Si_2O_8).[8H_2O]$
	Laumontite	$Ca(AlO_2H_2)_2(Si_2O_5)_2.[2H_2O]$
The Epidote Group	Milarite	$HKCa_2Al_2(Si_2O_5)_6$
	Zoisite	$Ca_2Al_2(AlOH)(SiO_4)_3$
	Clinozoisite	$Ca_2Al_2(AlOH)(SiO_4)_3$
	Epidote	$Ca_2Al_2(AlOH)(SiO_4)_3$ $Ca_2Fe_2(FeOH)(SiO_4)_3$
	Hancockite	$(Pb,Ca,Sr)_2(Al,Fe)_2(AlOH)(SiO_4)_3$
	Allanite	$(Ca,Fe)_2(Al,Ce,Fe)_2(AlOH)(SiO_4)_3$
	Prehnite	$H_2Ca_2Al_2(SiO_4)_3$
	Lawsonite	$Ca(AlO_2H_2)_2(SiO_3)_2$
	Carpholite	$Mn(AlO_2H_2)_2(SiO_3)_2$
	Cerite	$(Ca,Fe)Ce_2(OH)_3(CeO)(SiO_3)_3$
	Danburite	$CaB_2(SiO_4)_2$

R‴-silicates (*continued*)—

	Euclase	$Be(AlOH)SiO_4$
	Datolite	$Ca(BOH)SiO_4$
	Homilite	$Ca_2Fe''(BO)_2(SiO_4)_2$
	Gadolinite	$Be_2Fe''(YO)_2(SiO_4)_2$
	Axinite	$H(Ca,Fe)_3Al_2B(SiO_4)_4$
	Tourmaline	$(Na_6,Mg_3,Al_2)_3(Al,Fe)_6(BOH)_4Si_8O_{38}$
	Vesuvianite	$Ca_6Al_2(AlOH)(SiO_4)_5$
	Ilvaite	$CaFe''_2(Fe'''OH)(SiO_4)_2$
	Kentrolite	$Pb_2(Mn'''O)_2Si_2O_7$
	Melanotekite	$Pb_2(Fe'''O)_2Si_2O_7$
	Staurolite	$Fe''(AlO)_4(AlOH)(SiO_4)_2$
The Clintonite Group	Margarite	$H_2CaAl_4Si_2O_{12}$
	Chloritoid	$H_2(Fe,Mg)Al_2SiO_7$
	Clintonite	$H_3(Mg,Ca)_5Al_5Si_2O_{18}$
The Chlorite Group	[Serpentine	$H_4Mg_3Si_2O_9$] . . . Sp
	Pennine	Sp_3At_2 to SpAt
	Clinochlore	SpAt to Sp_2At_3
	Prochlorite	Sp_2At_3 to Sp_3At_7
	Amesite	$H_4Mg_2Al_2SiO_9$ . . . At
	Cronstedtite	$H_8Fe''_4Fe'''_4Si_3O_{20}$
	Beryl	$Be_3Al_2(SiO_3)_6$
	Cordierite	$(Mg,Fe)_4Al_3(OH)_2(Si_2O_7)_5$
	Barylite	$Ba_4Al_4Si_7O_{24}$
The Garnet Group	Grossular	$Ca_3Al_2(SiO_4)_3$
	Pyrope	$Mg_3Al_2(SiO_4)_3$
	Spessartite	$Mn_3Al_2(SiO_4)_3$
	Almandine	$Fe_3Al_2(SiO_4)_3$
	Uvarovite	$Ca_3Cr_2(SiO_4)_3$
	Andradite	$Ca_3Fe_2(SiO_4)_3$
	Kornerupine	$MgAl_2SiO_6$
	Sapphirine	$Mg_5Al_{12}Si_2O_{27}$

R⁗-silicates—

The Zircon Group	Zircon	$ZrSiO_4$
	Thorite	$ThSiO_4$
	Elpidite	$H_6Na_2Zr(SiO_3)_6$
	Catapleiite	$H_4Na_2ZrSi_3O_{11}$
	Stokesite	$H_4CaSnSi_3O_{11}$
	Eudialyte	$Na_4(Ca,Fe)_3Zr(SiO_3)_7$

Miscellaneous silicates—

The Helvite Group	Helvite	$(Mn,Fe)_2(Mn_2S)Be_3(SiO_4)_3$
	Danalite	$(Zn,Fe)_2(Fe_2S)Be_3(SiO_4)_3$
	Thaumasite	$CaSiO_3.CaCO_3.CaSO_4.15H_2O$
	Pyrosmalite	$H_7(MnCl)(Fe,Mn)_4(SiO_4)_4$
	Friedelite	$H_7(MnCl)Mn_4(SiO_4)_4$
	Dysanalyte	$6(Ca,Fe)TiO_3.(Ca,Fe)Nb_2O_6$

Class XI.—Nitrates and Iodates

Nitratine	$NaNO_3$
Nitre	KNO_3
Lautarite	$Ca(IO_3)_2$
Gerhardtite	$Cu_2(OH)_3NO_3$
Darapskite	$NaNO_3.Na_2SO_4.H_2O$

Class XII.—Phosphates, Arsenates, Vanadates, etc.

R′-phosphates—		
	Stercorite	$H(NH_4)NaPO_4.4H_2O$
R″-phosphates—		
	Monetite	$HCaPO_4$
	Hewettite	$H_2CaV_6O_{17}.8H_2O$
	Haidingerite	$HCaAsO_4.H_2O$
The Pharmacolite Group	Brushite	$HCaPO_4.2H_2O$
	Pharmacolite	$HCaAsO_4.2H_2O$
	Newberyite	$HMgPO_4.3H_2O$
	Wapplerite	$2HCaAsO_4.7H_2O$
	Hureaulite	$H_2Mn''_5(PO_4)_4.4H_2O$
	Graftonite	$(Fe,Mn,Ca)_3(PO_4)_2$
	Berzeliite	$(Ca,Mg,Mn)_3(AsO_4)_2$
	Fillowite / Dickinsonite	$3(Mn,Fe,Na_2)_3(PO_4)_2.H_2O$
	Fairfieldite	$Ca_2Mn(PO_4)_2.2H_2O$
	Brandtite	$Ca_2Mn(AsO_4)_2.2H_2O$
	Roselite	$(Ca,Co,Mg)_3(AsO_4)_2.2H_2O$
	Reddingite	$(Mn,Fe)_3(PO_4)_2.3H_2O$
	Hopeite / Parahopeite	$Zn_3(PO_4)_2.4H_2O$
	Anapaite	$(Ca,Fe)_3(PO_4)_2.4H_2O$
The Vivianite Group	Vivianite	$Fe_3(PO_4)_2.8H_2O$
	Symplesite	$Fe_3(AsO_4)_2.8H_2O$
	Erythrite	$Co_3(AsO_4)_2.8H_2O$
	Annabergite	$Ni_3(AsO_4)_2.8H_2O$
The Olivenite Group	Libethenite	$Cu(CuOH)PO_4$
	Olivenite	$Cu(CuOH)AsO_4$
	Adamite	$Zn(ZnOH)AsO_4$
	Descloizite	$(Pb,Zn)_2(OH)VO_4$
	Herderite	$CaBe(F,OH)PO_4$
The Wagnerite Group	Wagnerite	$Mg(MgF)PO_4$
	Triplite	$(Fe,Mn)_2FPO_4$
	Triploidite	$(Mn,Fe)_2(OH)PO_4$
	Tilasite	$Ca(MgF)AsO_4$
	Adelite	$Ca(MgOH)AsO_4$
	Sarcinite	$Mn(MnOH)AsO_4$
	Tarbuttite	$Zn(ZnOH)PO_4$
	Dihydrite	$Cu(CuOH)_4(AsO_4)_2$
	Clinoclase	$(CuOH)_3AsO_4$
The Apatite Group	Apatite	$Ca_4(CaF)(PO_4)_3$
	Svabite	$Ca_4(Ca(F,OH))(AsO_4)_3$
	Pyromorphite	$Pb_4(PbCl)(PO_4)_3$
	Mimetite	$Pb_4(PbCl)(AsO_4)_3$
	Vanadinite	$Pb_4(PbCl)(VO_4)_3$
	Allactite	$Mn''_7(OH)_8(AsO_4)_2$
	Hæmafibrite	$(MnOH)_3AsO_4.H_2O$
	Tagilite	$Cu(CuOH)PO_4.H_2O$
	Spencerite	$2Zn(ZnOH)PO_4.3H_2O$
	Conichalcite	$4(Cu,Ca)(CuOH)AsO_4.H_2O$
	Euchroite	$Cu(CuOH)AsO_4.3H_2O$
	Cornwallite	$Cu(CuOH)_4(AsO_4)_2.H_2O$

R″-phosphates (*continued*)—

	Tyrolite	$Cu(CuOH)_4(AsO_4)_2.7H_2O$
	Ludlamite	$Fe''_5(Fe''OH)_2(PO_4)_4.8H_2O$
	Hannayite	$H_4(NH_4)_2Mg_3(PO_4)_4.8H_2O$
	Beryllonite	$NaBePO_4$
The Triphylite Group	Natrophilite	$NaMnPO_4$
	Lithiophilite	$Li(Mn,Fe)PO_4$
	Triphylite	$Li(Fe,Mn)PO_4$
	Struvite	$(NH_4)MgPO_4.6H_2O$

R‴-phosphates—

	Pucherite	$BiVO_4$
	Xenotime	YPO_4
	Monazite	$(Ce,La,Di)PO_4$
	Rhabdophane	$(La,Di,Y)PO_4.H_2O$
	Churchite	$CePO_4.2H_2O$
	Strengite	$Fe'''PO_4.2H_2O$
	Scorodite	$Fe'''AsO_4.2H_2O$
	Phosphosiderite	$4Fe'''PO_4.7H_2O$
	Variscite / Lucinite	$AlPO_4.2H_2O$
	Augelite	$Al_2(OH)_3PO_4$
	Florencite	$(Al,Ce)_2(OH)_3PO_4$
	Dufrenite	$Fe'''_2(OH)_3PO_4$
	Atelestite	$(BiO)_2(BiO_2H_2)AsO_4$
	Peganite	$2Al_2(OH)_3PO_4.3H_2O$
	Eleonorite	$2(Fe'''OH)_3(PO_4)_2.5H_2O$
	Wavellite	$2(AlOH)_3(PO_4)_2.9H_2O$
	Cacoxenite	$2Fe'''_2(OH)_3PO_4.9H_2O$
	Pharmacosiderite	$2Fe'''AsO_4.Fe'''(OK)_3.5H_2O$
	Amblygonite	$Li(AlF)PO_4$
	Fremontite	$Na(AlF)PO_4$
	Durangite	$Na(AlF)AsO_4$
	Lazulite	$(Fe,Mg)(AlOH)_2(PO_4)_2$
	Arseniosiderite	$Ca_3Fe'''_4(OH)_9(AsO_4)_3$
	Synadelphite	$5Mn(OH)_2.2AlAsO_4$
	Hæmatolite	$4Mn(OH)_2.AlAsO_4$
	Flinkite	$2Mn(OH)_2.Mn'''AsO_4$
	Hamlinite	$SrAl_3(OH)_7P_2O_7$
The Childrenite Group	Childrenite	$Fe''Al(OH)_2PO_4.H_2O$
	Eosphorite	$MnAl(OH)_2PO_4.H_2O$
	Chalcosiderite	$CuFe'''_2(Fe'''O)_4(PO_4)_4.9H_2O$
	Turquoise	$CuAl_2(AlO)_4(PO_4)_4.9H_2O$
	Liroconite	$Cu_9Al_4(OH)_{15}(AsO_4)_5.20H_2O$

R‴‴‴-phosphates—

The Torbernite Group	Torbernite	$Cu(UO_2)_2(PO_4)_2.8H_2O$
	Zeunerite	$Cu(UO_2)_2(AsO_4)_2.8H_2O$
	Uranocircite	$Ba(UO_2)_2(PO_4)_2.8H_2O$
	Autunite	$Ca(UO_2)_2(PO_4)_2.8H_2O$
	Uranospinite	$Ca(UO_2)_2(AsO_4)_2.8H_2O$

Miscellaneous phosphates—

The Beudantite Group	Svanbergite	$Sr(AlO_2H_2)_3(PO_4)(SO_4)$
	Hinsdalite	$Pb(AlO_2H_2)_3(PO_4)(SO_4)$
	Corkite	$Pb(Fe'''O_2H_2)_3(PO_4)(SO_4)$
	Beudantite	$Pb(Fe'''O_2H_2)_3(AsO_4)(SO_4)$

Miscellaneous-phosphates (*continued*)—

Chalcophyllite	Hydr. arsenate and sulphate of Cu
Dahllite	$4Ca_3(PO_4)_2.2CaCO_3.H_2O$

Antimonates—

Monimolite	$Pb_3(SbO_4)_2$
Schneebergite	$(Ca_2O)(SbO)SbO_4$
Atopite	$Ca_2Sb_2O_7$
Tripuhyite	$Fe''_2Sb_2O_7$
Lewisite	$(Ca,Fe)_5Ti_4Sb_6O_{24}$
Derbylite	$Fe''Sb_2O_6.5Fe''TiO_3$

Antimonites—

Romeite	$Ca(SbO_2)_2$
Nadorite	$(PbCl)SbO_2$

Class XIII.—Niobates, Tantalates, etc.

Fergusonite	$(Y,Er,Ce)(Nb,Ta)O_4$
Microlite	$Ca_2(Ta,Nb)_2O_7$
Samarskite	$(Fe,Ca,UO_2)_3(Y,Er,Ce)_2((Nb,Ta)_2O_7)_3$
Yttrotantalite	$Y_4(Ta_2O_7)_3$
Koppite	$K_4Ca_3(CaF)(CeO)(Nb_2O_7)_3$
Columbite	$(Fe,Mn)(NbO_3)_2$
Tantalite	$(Fe,Mn)(Ta,Nb)_2O_6$
Tapiolite	$Fe(Ta,Nb)_2O_6$
Mossite	$Fe(Nb,Ta)_2O_6$
Stibiocolumbite	$(SbO)_2(Nb,Ta)_2O_6$
Stibiotantalite	$(SbO)_2(Ta,Nb)_2O_6$
Strüverite	$Fe(Ta,Nb)_2O_6$ + TiO_2
Ilmenorutile	$Fe(Nb,Ta)_2O_6$ + TiO_2
Ainalite	$Fe(Nb,Ta)_2O_6$ + SnO_2
Æschynite	$(Ce,La,Er)_2Nb_4O_{13}.(Ce,La,Er)_2(Ti,Th)_5O_{18}$
Polycrase, Euxenite, Blomstrandine, Priorite, Pyrochlore	Niobates and titanates of Y, Er, Ce, U, etc.

Class XIV.—Sulphates

R′-sulphates—

Misenite	$HKSO_4$
Mascagnite	$(NH_4)_2SO_4$
Thenardite	Na_2SO_4
Aphthitalite	$(K,Na)_2SO_4$
Mirabilite	$Na_2SO_4.10H_2O$

R″-sulphates—

The Barytes Group

Barytes	$BaSO_4$
Celestite	$SrSO$
Anglesite	$PbSO_4$
Anhydrite	$CaSO_4$
Kieserite	$MgSO_4.H_2O$
Ferropallidite	$FeSO_4.H_2O$
Gypsum	$CaSO_4.2H_2O$
Chalcanthite	$CuSO_4.5H_2O$

R′-sulphates (*continued*)—

	Hexahydrite	$MgSO_4.6H_2O$
The Epsomite Group	Epsomite	$MgSO_4.7H_2O$
	Goslarite	$ZnSO_4.7H_2O$
	Morenosite	$NiSO_4.7H_2O$
The Melanterite Group	Mallardite	$MnSO_4.7H_2O$
	Melanterite	$FeSO_4.7H_2O$
	Bieberite	$CoSO_4.7H_2O$
	Boothite	$CuSO_4.7H_2O$
	Dolerophanite	$(Cu_2O)SO_4$
	Lanarkite	$(Pb_2O)SO_4$
	Stelznerite	$Cu_3(OH)_4SO_4$
	Brochantite	$Cu_4(OH)_6SO_4$
	Linarite	$PbCu(OH)_2SO_4$
	Langite	$Cu_4(OH)_6SO_4.H_2O$
	Herrengrundite	$CaCu_4(OH)_6(SO_4)_2.3H_2O$
	Glauberite	$Na_2Ca(SO_4)_2$
	Langbeinite	$K_2Mg_2(SO_4)_3$
	Syngenite	$K_2Ca(SO_4)_2.H_2O$
	Kröhnkite	$Na_2Cu(SO_4)_2.2H_2O$
	Blödite	$Na_2Mg(SO_4)_2.4H_2O$
	Leonite	$K_2Mg(SO_4)_2.4H_2O$
	Löweite	$Na_4Mg_2(SO_4)_4.5H_2O$
	Picromerite	$K_2Mg(SO_4)_2.6H_2O$
	Polyhalite	$K_2Ca_2Mg(SO_4)_4.2H_2O$
	Natrochalcite	$Na_2Cu_2(CuOH)_2(SO_4)_4.2H_2O$

R‴-sulphates—

	Alunogen	$Al_2(SO_4)_3.18H_2O$
	Coquimbite	$Fe_2(SO_4)_3.9H_2O$
	Halotrichite	$Fe'''Al_2(SO_4)_4.24H_2O$
	Alumian	$Al(AlO)(SO_4)_2$
	Aluminite	$(AlO)_2SO_4.9H_2O$
	Amarantite	$Fe'''(Fe'''O)(SO_4)_2.7H_2O$
	Castanite	$Fe'''(Fe'''O)(SO_4)_2.8H_2O$
	Copiapite	$Fe'''_3(Fe'''O)(SO_4)_5.18H_2O$
	Kalinite	$KAl(SO_4)_2.12H_2O$
	Tschermigite	$(NH_4)Al(SO_4)_2.12H_2O$
	Ferronatrite	$Na_3Fe'''(SO_4)_3.3H_2O$
The Alunite Group	Alunite	$K(AlO_2H_2)_3(SO_4)_2$
	Jarosite	$K(Fe'''O_2H_2)_3(SO_4)_2$
	Natrojarosite	$Na(Fe'''O_2H_2)_3(SO_4)_2$
	Plumbojarosite	$Pb(Fe'''O_2H_2)_6(SO_4)_4$
	Carphosiderite	$H(Fe'''O_2H_2)_3(SO_4)_2$
	Sideronatrite	$Na_2(Fe'''OH)(SO_4)_2.3H_2O$
	Römerite	$H_2(MgOH)_2(Fe'''OH)_2(SO_4)_4.12H_2O$
	Botryogen	$H_2(Fe,Zn)(Fe'''OH)_2(SO_4)_4.12H_2O$
	Pickeringite	$MgAl_2(SO_4)_4.22H_2O$

Miscellaneous Sulphates—

Spangolite	$Cu_6(AlCl)(OH)_{12}SO_4.3H_2O$
Connellite	$Cu_{15}(Cl,OH)_4SO_{16}.15H_2O$
Caracolite	$Na_2SO_4.Pb(OH)Cl$
Leadhillite	$PbSO_4.Pb(PbOH)_2(CO_3)_2$
Caledonite	$5Pb(PbOH)_6(SO_4)_4.2Cu(CuOH)_6(CO_3)_4$

Miscellaneous Sulphates (*continued*)—

Kainite	$MgSO_4.KCl.3H_2O$
Sulphohalite	$2Na_2SO_4.NaCl.NaF$
Hanksite	$4Na_2SO_4.Na_2CO_3$
Johannite	Sulphate of uranium

Class XV.—Tellurates, etc.

Montanite	$Bi_2(OH)_4TeO_4$
Chalcomenite	$CuSeO_3.2H_2O$

Class XVI.—Chromates

Crocoite	$PbCrO_4$
Phœnicochroite	$Pb(Pb_2O)(CrO_4)_2$
Vauquelinite	$2(Pb, Cu)CrO_4.(Pb, Cu)_3(PO_4)_2$

Class XVII.—Molybdates and Tungstates

The Scheelite Group	Wulfenite	$PbMoO_4$
	Powellite	$Ca(Mo,W)O_4$
	Stolzite	$PbWO_4$
	Cuprotungstite	$CuWO_4$
	Scheelite	$CaWO_4$
	Raspite	$PbWO_4$
The Wolframite Group	Hübnerite	$MnWO_4$
	Wolframite	$(Fe,Mn)WO_4$
	Ferberite	$FeWO_4$

Class XVIII.—Uranates

Uraninite	Uranate of uranium

TABLES OF REACTIONS

TABLE A

Colour imparted to Flame

1.	Yellow	Sodium	Given by even the minutest traces.
2.	Reddish-yellow	Calcium	Not easily obtained in many minerals.
3.	Pale violet	Potassium	Easily masked by sodium, unless observed through blue glass. Silicates should be mixed with gypsum.
4.	Crimson	Lithium	Not given by many minerals besides Lepidolite, Spodumene, Petalite, Tourmaline. Silicates should be mixed with gypsum.
5.	Carmine	Strontium	Not given by many minerals besides Celestite, Strontianite. (Silicates do not show it.)
6.	Emerald-green	Copper	Blue if the mineral be moistened with HCl.
7.	Bluish-green	Phosphorus	(Phosphates). The mineral should be moistened with sulphuric acid.
8.	Yellowish-green	Boron	(Borates or borosilicates). The mineral is to be mixed with fluor and potassium bisulphate. A somewhat similar colour is given by carbonate or sulphate of barium and by oxide or sulphide of molybdenum.

TABLE B

Sublimates in Closed Tube

1. Water ; given by all hydrated salts and those which contain hydroxyl ; sometimes acid.
2. Metallic liquid globules of Mercury ; given by most minerals containing mercury, if previously mixed with sodium carbonate.
3. Yellow drops of Sulphur ; given by native sulphur, by pyrites and other disulphides, and in a less degree by some of the other sulphides.
4. Metallic mirror of Arsenic ; given by arsenic and many arsenides, arsenosulphides, etc. ; when the bottom of the tube is broken and the mirror heated it gives a white sublimate of As_2O_3, and an odour of garlic is noticeable.
5. Reddish sublimate of Antimony Oxy-sulphide ; given by sulphide of antimony and many sulphantimonites.
6. Dark red and yellow fusible drops of Arsenic Sulphide ; given by sulphides of arsenic and many of the sulpharsenites.
7. Black sublimate (changing to red when rubbed) of Mercury Sulphide ; given by minerals containing sulphur and mercury.
8. Black fusible globules of Selenium or Tellurium, or white or colourless globules of TeO_2 ; given by some minerals containing selenium or tellurium.

TABLE C

Sublimates in Open Tube

1. White volatile crystalline (octahedra) As_2O_3 ; given by arsenic, arsenic sulphides, arsenides, arsenosulphides and sulpharsenites.
2. White amorphous infusible Antimony Oxides ; given by most minerals containing antimony ; often accompanied by white volatile crystalline oxide of antimony.
3. White or greyish Tellurium Oxide, which may be fused to clear drops; given by most minerals containing tellurium (tellurides).
4. White volatile crystalline Selenium Oxide ; given by many minerals containing selenium (selenides) ; it is often coloured reddish by Selenium.
5. Brown (changing to yellow when cold) fusible Bismuth Oxide ; given by most minerals containing bismuth (sulphobismuthites).
6. Pale yellow (changing to white when cold) crystalline network of Molybdenum Oxide ; given by oxide and sulphide of molybdenum.

TABLE D

Vapours in Open Tube

1. Acid fumes with a pungent sulphurous odour indicate Sulphur.
2. White fumes and a strong garlic odour indicate Arsenic.
3. Dense white fumes indicate Antimony.
4. Fumes having a strong horse-radish odour indicate Selenium (selenides).

TABLE E

Incrustations on Charcoal

1. White, distant from the assay, readily volatilised, with a garlic odour—Arsenic (arsenates, arsenides, etc.).
2. White, near the assay, volatile—Antimony (antimonides and sulphantimonites). A very similar incrustation is sometimes given by lead sulphide.
3. Yellow while hot, white on cooling ; not volatile in the oxidising flame—Zinc. Moistened with cobalt nitrate and ignited it becomes green.
4. Faint yellow while hot, white on cooling ; not volatile in the oxidising flame—Tin (not given by many minerals besides Cassiterite, Stannite). Moistened with cobalt nitrate and ignited it becomes bluish-green.
5. Yellow ; volatile—Lead.
6. Dark yellow, fainter on cooling ; volatile—Bismuth (sulpho-bismuthites).
7. Reddish-brown, volatile — Cadmium (not given by many minerals besides Greenockite).
8. Red—Silver, in presence of lead and antimony.

Whitish incrustations are also given by Se, Tl, Te, Mo, etc.

TABLE F

Metallic Globule (or Scales) on Charcoal

1. Brittle—Antimony.
2. Bright and malleable—Tin.
3. Malleable, easily fusible ; leaves a mark on paper—Lead.
4. Brittle and fusible—Bismuth.
5. White and malleable—Silver.
6. Copper-red—Copper.
7. Yellow—Gold.

TABLE G

Colour of Borax Bead

Oxidising Flame.	Reducing Flame.	Indicates.
1. Blue.	Blue.	Cobalt.
2. Green when hot, blue when cold.	Colourless; opaque red with much of the substance.	Copper.
3. Orange-red to yellow.	Green.	Chromium.
4. Brownish-red when hot, yellow when cold.	Green when cold.	Iron; also (paler) Uranium.
5. Violet when hot, brown when cold.	Greyish, opaque.	Nickel.
6. Yellowish when hot, colourless when cold.	Colourless or grey.	Bismuth.
7. Amethyst.	Nearly colourless.	Manganese.
8. Yellow when hot, greenish when cold.	Brownish when hot, green when cold.	Vanadium.
9. Yellow when hot, colourless when cold.	Yellowish-brown.	Titanium.
10. Colourless.	Brown.	Molybdenum.
11. Colourless.	Yellow to brown.	Tungsten.
12. Rose.	Rose.	Didymium.
13. Yellow.	Colourless.	Cerium.

TABLE H

Colour of Microcosmic Salt Bead

Oxidising Flame.	Reducing Flame.	Indicates.
1. Red to yellow.	Red to yellow.	Nickel.
2. Greenish.	Green.	Molybdenum.
3. Yellow to Green.	Green.	Uranium.
4. Colourless.	Yellow, violet when cold.	Titanium.
5. Colourless.	Brown.	Niobium.
6. Yellow to colourless.	Blue.	Tungsten.
7. Green.	Green.	Chromium.
8. Yellow.	Green.	Vanadium.

Microcosmic salt is especially useful in the detection of silicates, which are all decomposed by it; the metallic oxides are dissolved while the silica remains as an insoluble cloud especially noticeable while the bead is hot.

TABLE K

Colour of Residue heated with Cobalt Nitrate

1. Red indicates Magnesium (the residue glows during ignition).
   „ „ Barium (red while hot).
   „ „ Tantalum (red when cold).
2. Green „ Zinc (except the silicates).
   „ „ Titanium (yellowish).
   „ „ Tin (bluish).
3. Violet „ Zirconium.
4. Blue „ Aluminium (also zinc silicates).

The only reliable reactions are those of Zinc and Aluminium.

TABLES OF PHYSICAL PROPERTIES

(Names in italics are not mentioned in the list on pp. 601-616.)

TABLE I

Minerals arranged according to their Mean Refractive Index

(The numbers relate to Na-light unless otherwise stated.)

1·31, Ice.
1·33, Villiaumite.
1·34, Cryolithionite.
1·35, Chiolite.
,, Cryolite.
1·38, Sellaite.
1·41, Thomsenolite.
1·43, Fluor.
,, Ralstonite.
1·45, Opal.
,, Epsomite.
1·46, Kalinite.
,, Kieserite.
,, Yttrofluorite.
,, Nosean.
,, Sassolite.
,, Nitratine.
1·47, Gmelinite.
,, Borax.
,, Fluellite.
,, Thenardite.
,, Melanterite.
,, Picromerite.
,, Aluminite.
,, Carnallite.
,, *Boussingaultite.*
1·48, Tridymite.
,, Goslarite.
,, *Faujasite.*
,, Phillipsite.
,, Natrolite.
,, Morenosite.
,, Löweite.
,, Blödite.
,, Sodalite.
1·49, Thaumasite.
,, *Stellerite.*
,, Hackmanite.
,, Cristobalite.
,, Analcite.
,, Sylvite.
,, Allophane.
,, *Cyanochroite.*
,, Aphthitalite.
1·50, Nitre.
1·50, Stilbite.
,, Scolecite.
,, Haüyne.
,, Mesolite.
,, Chabazite.
,, *Didymolite.*
,, *Levyne.*
,, Ulexite.
,, Heulandite.
,, Nesquehonite.
,, Struvite.
,, Prosopite.
1·51, Trona.
,, Kainite.
,, Ussingite.
,, *Tychite.*
,, Leucite.
,, Thomsonite.
,, Harmotome.
,, Inyoite.
,, Petalite.
,, *Epistilbite.*
,, Brewsterite.
,, Northupite.
1·52, Cancrinite.
,, Syngenite.
,, *Davyne.*
,, Newberyite.
,, *Hautefeuillite.*
,, Gaylussite.
,, Laumontite.
,, *Brugnatellite.*
,, *Mellite.*
,, Orthoclase.
,, Pollucite.
1·53, Microcline.
,, Anorthoclase.
,, Heintzite.
,, Gypsum.
,, Pirssonite.
,, *Fischerite.*
,, Hydromagnesite.
,, Albite.
,, Langbeinite.
,, Chalcanthite.
1·53, Apophyllite.
1·54, Nepheline.
,, Meyerhofferite.
,, *Artinite.*
,, Dawsonite.
,, *Stichtite.*
,, *Gismondite.*
,, Hyalophane.
,, Sulphoborite.
,, Oligoclase.
,, Kaolinite.
,, Cordierite.
,, Salt.
1·55, Botryogen.
,, *Johnstrupite.*
,, Eudidymite.
,, Quartz.
,, Edingtonite.
,, Hydrargillite.
,, Chalcedony.
,, Andesine.
,, Polyhalite.
,, *Dipyre.*
,, Coquimbite.
,, *Mizzonite.*
1·56, Beryllonite.
,, *Whewellite.*
,, Variscite.
,, *Ježekite.*
,, Gyrolite.
,, Labradorite.
,, Talc.
1·57, Pinnoite.
,, Epididymite.
,, Brucite.
,, Serpentine.
,, *Narsarsukite.*
,, Calcite.
,, Wagnerite.
,, *Fibroferrite.*
,, *Bastite.*
,, Marialite.
,, Bauxite.
,, *Pandermite.*
,, Alunite.

1·58, Pennine.
,, Kröhnkite.
,, *Bavenite.*
,, Meionite.
,, Augelite.
,, Anorthite.
,, Scapolite.
,, Pyrophyllite.
,, Cacoxenite.
,, *Corundophilite.*
,, Ferronatrite.
1·59, Beryl.
,, Rinneite.
,, *Custerite.*
,, Celsian.
,, Chlormanganokalite.
,, Hopeite.
,, Anhydrite.
,, Colemanite.
,, Leucophane.
,, Muscovite.
,, Clinochlore.
,, Pharmacolite.
,, Zinnwaldite.
,, Sussexite.
,, *Garnierite.*
,, Amblygonite.
,, Dolomite.
,, Hambergite.
1·60, Lepidolite.
,, Vivianite.
,, Bertrandite.
,, *Cebollite.*
,, Paragonite.
,, Biotite.
,, Humite.
,, *Meliphane.*
1·61, Eudialyte.
,, Phlogopite.
,, Hillebrandite.
,, Torbernite.
,, Stokesite.
,, *Pitticite.*
,, *Gummite.*
,, *Glauconite.*
,, Turquoise.
,, Pectolite.
1·62, Herderite.
,, *Bazzite.*
,, Topaz.
,, Tremolite.
,, Schizolite.
,, *Eucolite.*
,, Uranocircite.
1·62, Autunite.
,, *Nephrite.*
,, Hemimorphite.
,, Chondrodite.
,, Celestite.
,, Lazulite.
1·63, Carpholite.
,, Tourmaline.
,, Actinolite.
,, Hamlinite.
,, Prehnite.
,, *Richterite.*
,, *Gedrite.*
,, Wollastonite.
,, *Celadonite.*
,, *Pargasite.*
,, Annabergite.
,, Erythrite.
,, Melilite.
,, Anthophyllite.
,, Danburite.
,, *Grandidierite.*
1·64, Andalusite.
,, Barytes.
,, *Uralite.*
,, Zeunerite.
,, Sal-ammoniac.
,, Apatite.
,, Glaucophane.
,, Margarite.
,, Sarcolite.
1·65, Datolite.
,, Hornblende.
,, *Stewartite.*
,, *Palaite.*
,, Clintonite.
1·66, Tellurite.
,, *Salmonsite.*
,, Forsterite.
,, Hardystonite.
,, Euclase.
,, Strontianite.
,, *Leucosphenite.*
,, Pyrosmalite.
,, Natrochalcite.
,, Jadeite.
,, Tilasite.
,, Phenacite.
,, Sillimanite.
1·67, Spodumene.
,, Boracite.
,, Cordylite.
,, Hinsdalite.
,, *Hibschite.*
1·67, Alstonite.
,, *Rinkite.*
,, Spangolite.
,, Enstatite.
,, *Spurrite.*
,, Monticellite.
,, Gehlenite.
,, Haidingerite.
,, Adelite.
,, Witherite.
,, Lawsonite.
,, Kornerupine.
1·68, Axinite.
,, Olivine.
,, Aragonite.
,, Triphylite.
,, Barylite.
,, *Diallage.*
,, *Harstigite.*
,, Diopside.
1·69, Barytocalcite.
,, Dumortierite.
,, *Troostite.*
,, *Wöhlerite.*
,, *Fuggerite.*
,, Dioptase.
1·70, Hypersthene.
,, *Serendibite.*
,, Tyrolite.
,, Euchroite.
,, Gadolinite.
,, *Barkevikite.*
,, Gerhardtite.
,, Astrophyllite.
,, Zoisite.
,, Willemite.
1·71, *Arfvedsonite.*
,, Pharmacosiderite.
,, Rhodochrosite.
,, Spinel.
,, Sapphirine.
1·72, Vesuvianite.
,, Parisite.
,, Glaucochroite.
,, Clinozoisite.
,, Magnesite.
,, Chloritoid.
,, Babingtonite.
,, *Pajsbergite.*
,, Xenotime.
,, Cyanite.
,, Trimerite.
,, Rhodonite.
,, Augite.

1·72, Diaspore.
„ Hæmatolite.
1·73, Calamine.
„ *Ottrelite.*
„ *Ganophyllite.*
„ *Piedmontite.*
„ *Sicklerite.*
„ Phosphosiderite.
1·74, Allanite.
„ Bastnäsite.
„ Connellite.
„ Periclase.
„ Ilvaite.
„ Thalenite.
„ Helvite.
„ Staurolite.
„ Hedenbergite.
„ Libethenite.
1·75, Chrysoberyl.
„ Chalybite.
„ Arsenolite.
„ *Pleonaste.*
1·76, Grossular.
„ Chessylite.
„ Epidote.
„ Corundum.
„ *Shattuckite.*
„ Lorenzenite.
1·77, Gahnite.
„ Pyrope.
1·78, Inesite.
„ Ænigmatite.
„ Hercynite.
„ Benitoite.
1·78, *Hessonite.*
„ Almandine.
1·79, Allactite.
„ *Molybdophyllite.*
„ *Ardennite.*
1·80, Tephroite.
„ Acmite.
1·81, Spessartite.
„ Strengite.
„ Monazite.
1·82, *Pascoite.*
1·83, Uvarovite.
„ Olivenite.
„ Descloizite.
„ Linarite.
1·84, Scorodite.
„ Fayalite.
1·85, Caledonite.
„ Paratacamite (green).
1·88, Malachite.
„ Anglesite.
„ *Uvanite.*
1·89, Titanite.
1·92, Scheelite.
1·95, Zircon.
1·96, Alamosite.
2·01, Zincite.
2·04, Cassiterite.
„ Sulphur.
2·06, Pyromorphite.
„ Cerargyrite.
2·07, Cerussite.
2·09, Schneebergite.
„ Senarmontite.
2·10, *Metahewettite.*
2·12, Laurionite.
2·13, Phosgenite.
2·14, Mimetite.
2·15, Paralaurionite.
2·18, Iodyrite.
„ Hewettite (red).
2·22, Stolzite.
2·25, Bromargyrite.
2·31, Calomel.
2·33, Vanadinite (red).
2·35, Pyrophanite.
„ Marshite.
„ Wulfenite.
2·37, Blende.
2·38, Perovskite.
2·40, Stibiotantalite.
2·42, Diamond.
„ Stibiocolumbite.
„ Crocoite.
2·50, Göthite.
2·53, Anatase.
2·55, *Köchlinite* (red).
2·59, Brookite.
2·60, Raspite.
2·69, Greenockite.
2·76, Rutile.
2·85, Cuprite (red).
2·94, Proustite.
2·98, Pyrargyrite (red).
„ Cinnabar (red).
3·18, Hutchinsonite.
3·27, Smithite.
4·04, Stibnite (red).

TABLE II

Minerals arranged according to their Birefringence

Uniaxial Positive

·0008 Rinneite.
·001 Gmelinite.
·002 Apophyllite.
·003 Pennine.
·004 Ice.
„ *Davyne.*
·005 Eudialyte.
·008 Aphthitalite.
„ Coquimbite.
·009 Quartz.
„ Hamlinite.
·010 Pinnoite.
·010 Iodyrite.
·012 Sellaite.
·016 Phenacite.
„ Sarcolite.
„ Scheelite.
·018 Tridymite.
·020 Zincite.
„ Wurtzite.
·021 Brucite.
·022 Connellite.
·026 Phosgenite.
·029 Willemite.
·031 *Narsarsukite.*
·047 Benitoite.
·055 Ferronatrite.
·056 Dioptase.
·062 Zircon.
·081 Parisite.
·099 Cassiterite.
·287 Rutile.
·327 Cinnabar (red).
·683 Calomel.

Uniaxial Negative

·001 Vesuvianite.
·002 Chabazite.
„ *Levyne.*
·003 *Eucolite.*
·004 Apatite.
·005 Nepheline.
„ Melilite.
·006 Gyrolite.
„ Chiolite.
·007 Beryl.
·008 Corundum.
·012 Pyromorphite.
„ Hardystonite.
·015 *Mizzonite.*
„ Mimetite.
·017 Tourmaline.
·018 Löweite.
·019 *Meliphane.*
·020 Boleite.
·021 Scapolite.
„ *Bazzite.*
·028 Cancrinite.
„ *Mellite.*
·032 Pseudoboleite.
·036 Meionite.
·038 Thaumasite.
·053 Spangolite.
·054 *Molybdophyllite.*
·055 Vanadinite (red).
·061 Anatase.
·086 Stolzite.
·098 Wulfenite.
·100 Cumengeite.
·172 Calcite.
·188 Cordylite.
·189 Dolomite.
·203 Pyrargyrite.
·222 Rhodochrosite.
·227 Calamine.
·241 Chalybite.
·250 Nitratine.
„ Hæmatite (red).
·268 Proustite.
·270 Pyrophanite.

Biaxial

·0004	Mesolite.	+	·010	Stokesite.	+	·017	Sulphoborite.	−
·002	Apophyllite.	+	„	*Salmonsite* (2V = 90°)		„	Syngenite.	−
·004	Blödite.	+				·018	Amblygonite.	−
„	Epididymite.	−	„	Trimerite.	−	·019	Euclase.	+
·005	Eudidymite.	+	„	*Epistilbite.*	−	„	Hedenbergite.	+
„	*Harstigite.*	+	„	Rhodonite.	−	„	Lawsonite.	+
„	Harmotome.	+	·011	Clinochlore.	+	„	Hinsdalite.	+
„	Hyalophane.	−	„	Boracite (2V = 90°)		„	*Pargasite.*	−
„	Danburite.	−	„	Andalusite.	−	·020	*Fouquéite.*	+
·006	Clinozoisite.	+	„	Dumortierite.	−	„	*Ardennite.*	+
„	Zoisite.	+	„	Serpentine.	−	·021	Augite.	+
„	Andesine.	+	„	*Stellerite.*		„	Spodumene.	+
„	Sapphirine.	−	·012	Brewsterite.	+	„	Sillimanite.	+
„	Stilbite.	−	„	Barytes.	+	„	Alamosite.	−
·007	Orthoclase.	−	„	*Custerite.*	+	·022	Glaucophane.	+
„	Microcline.	−	„	Petalite.	+	„	Hemimorphite.	+
„	Heulandite.	+	„	*Johnstrupite.*	+	„	Carpholite.	−
„	Oligoclase.	−	„	Laumontite.	−	„	Atacamite.	−
·008	Kaolinite.	−	„	Clintonite.	−	·023	Bertrandite.	−
„	Cordierite.	−	·013	Natrolite.	+	·024	Anthophyllite.	+
„	Labradorite.	−	„	Anorthite.	−	„	*Diallage.*	+
„	Thomsenolite.	−	„	Hypersthene.	−	„	*Ganophyllite.*	−
„	*Palaite* (2V = 90°)		„	Kornerupine.	−	·025	*Crocidolite.*	+
·009	Chrysoberyl.	+	„	Thalenite.	−	„	Wavellite.	+
„	Enstatite.	+	„	Wagnerite.	−	„	Morenosite.	−
„	Topaz.	+	·014	Augelite.	+	„	Inyoite.	−
„	Celestite.	+	„	Barylite.	+	„	Actinolite.	−
„	Axinite.	−	„	Wollastonite.	−	„	Borax.	−
„	Beryllonite.	−	·015	*Ottrelite.*	+	·026	Kainite.	+
·010	Albite.	+	„	Chloritoid.	+	„	*Stichtite.*	−
„	*Quartzine.*	+	„	Edingtonite.	−	·027	Carnallite.	+
„	Staurolite.	+	„	*Didymolite.*	−	„	Leucophane.	−
„	Celsian.	+	·016	Anglesite.	+	„	Goslarite.	−
„	Gypsum.	+	„	Cyanite.	−	·028	Colemanite.	+

·028	Thomsonite.	+
„	Botryogen.	+
„	Tremolite.	−
„	Epsomite.	−
·029	Herderite.	−
„	Jadeite.	+
·030	Diopside.	+
„	Realgar.	−
„	Chalcanthite.	−
„	*Låvenite.*	−
„	*Sicklerite.*	−
·031	Nesquehonite.	−
„	Schizolite.	+
·032	Chondrodite.	+
„	Variscite.	−
„	Allanite.	−
·033	Prehnite.	−
„	*Cebollite.*	+
·035	Tilasite.	−
036	Olivine.	+
„	Lazulite.	−
·037	*Grandidierite.*	−
„	Epidote.	−
·038	Pectolite.	+
„	Muscovite.	−
·039	*Spurrite.*	−
·040	Talc.	−
„	*Ježekite.*	−
„	Pyrophyllite.	−
·042	Heintzite.	+
„	Ussingite.	+
„	Fayalite.	−
·043	Anhydrite.	+
„	*Leucosphenite.*	+
·044	Biotite.	−
·045	Lorenzenite.	+
„	Monazite.	+
„	Datolite.	−
·048	Diaspore.	+
·049	Glaucochroite.	−
·050	Crocoite.	+
„	*Pascoite.*	−
·054	Vivianite.	+
·055	Astrophyllite.	+
„	*Artinite.*	−
·058	Kröhnkite.	−
·060	Meyerhofferite.	−
„	*Whewellite.*	+
„	*Stewartite.*	−
·061	Stibiocolumbite.	+
·065	Natrochalcite.	+
·066	*Shattuckite.*	
·069	Hydrargillite.	+
·070	Leadhillite.	−
·071	Pirssonite.	+
·072	Hornblende.	−
·074	Hambergite.	+
·081	Laurionite.	+
·083	Stibiotantalite.	+
·091	Okenite.	−
·108	Chessylite.	+
·110	Hutchinsonite.	−
·121	Titanite.	−
·130	Dawsonite.	−
·148	Witherite.	−
·152	Strontianite.	−
·156	Aragonite.	−
·160	Brookite.	+
·172	Nitre.	−
·200	*Molybdite.*	+
·240	*Uvanite.*	−
·254	Malachite.	−
·274	Cerussite.	−
·290	Sulphur.	+
·605	Hewettite (red).	−
1·109	Stibnite (red).	−

TABLE III

Minerals arranged according to the value of 2E

(*The angles relate to Na-light unless otherwise stated.*)

7° 51′	Biotite.	−
8° 58′	Nitre.	−
10°	Sassolite.	
10° 36′	Strontianite.	−
11° 8′	Glauberite (at 22° C.).	−
12° 6′	Alstonite.	−
13° 32′	Allactite.	−
17° 8′	Cerussite.	−
19°	Talc (red).	−
20° 23′	Clintonite (red).	−
20° 32′	Leadhillite (red).	−
20° 45′	Orthoclase (Sanidine) (red).	−
23° 15′	Barytocalcite (red).	−
26° 30′	Witherite (red).	−
28° 25′	Monazite.	+
30° 16′	Brookite.	+
30° 54′	Aragonite.	−
32°	Hinsdalite.	+
41° 53′	*Ganophyllite.*	−
44° 0′	Sillimanite (red).	+
44° 23′	Syngenite.	
47° 0′	Eudidymite.	+
48° 14′	Pirssonite.	+
49° 30′	*Grandidierite.*	−
49° 40′	Epididymite.	+
50° 25′	Zinnwaldite.	−
50° 34′	Dumortierite.	−
51° 38′	Gaylussite (red).	−
52° 24′	Laumontite (red).	−
52° 30′	Titanite.	+
55° 0′	Wapplerite.	
55° 44′	Scolecite.	−
59° 23′	Borax.	−
59° 24′	Cryolite.	+
59° 30′	Wagnerite.	−
60°	Ænigmatite.	+
60° 34′	Ussingite.	+
60° 56′	Struvite.	+
60° 57′	Autunite.	−
61° 11′	Euchroite.	+
63° 3′	Amarantite.	−
64° 1′	Barytes.	+
64° 22′	Morenosite.	−
65° 30′	Kornerupine.	−
66°	Herrengrundite.	−
66° 5′	*Serpierite.*	−
67° 37′	Hornblende (Basaltic).	−
67° 42′	Göthite.	−
69° 36′	Thomsenolite.	−
70°	Muscovite.	−
70°	Hæmafibrite.	+
70°	*Spurrite.*	
70°	*Ardennite.*	+
70° 20′	Newberyite.	+
70° 40′	Wollastonite (red).	−
71° 3′	Goslarite.	−
71° 30′	Anhydrite (red).	+
71° 40′	Anorthoclase.	−

72°	Baddeleyite.	−
72°	Lorenzenite.	+
74° 2′	Picromerite.	+
74° 15′	Leucophane.	−
74° 25′	Childrenite.	−
75° 35′	*Epistilbite.*	−
76° 12′	*Cyanochroite.*	+
77° 28′	*Boussingaultite.*	
77° 53′	*Rinkite.*	+
78° 18′	Epsomite.	−
78° 30′	*Bavenite.*	
78° 39′	Hemimorphite.	+
80°	*Corundophilite.*	+
82° 40′	Schizolite	+
83°	Sarcinite.	−
84° 15′	Nesquehonite.	−
84° 42′	Augelite.	+
84° 43′	Chrysoberyl.	+
85° 35′	Glaucophane.	+
86° 0′	Thomsonite (red).	+
86° 21′	Amblygonite.	−
87° 44′	Mascagnite (red).	+
87° 59′	Euclase.	+
88°	*Hautefeuillite.*	+
88° 38′	Celestite.	+
89° 18′	Malachite.	−
90° 0′	Kieserite.	+
90° 27′	*Harstigite.*	+
90° 28′	*Valléite.*	−
93° 1′	Chalcanthite.	−
94°	Brewsterite (red).	+
94°	Natrolite.	+
95°	*Crocidolite.*	+
95° 8′	Colemanite.	+
95° 14′	Gypsum (at 20° C.) (red).	+
100°	*Pascoite.*	−
101° 7′	Hypersthene.	−
102° 50′	Prosopite.	
104° 41′	Fayalite.	−
105°	*Custerite.*	+
106° 18′	*Fischerite.*	+
106° 40′	Adelite.	+
107° 30′	*Pargasite* (red).	+
108° 1′	Lanthanite (red).	−
108° 10′	Pyrophyllite (red).	−
108° 34′	Keilhauite.	+
111° 20′	Augite.	+
111° 50′	Chloritoid (red).	+
112° 12′	Diopside.	+
112° 42′	Natron.	−
113°	Variscite.	+
114° 30′	Margarite.	−
115° 6′	Carnallite.	+
120°	Pachnolite.	+
120° 12′	Orthoclase (Adularia).	−
120° 40′	Topaz.	+
120° 46′	Blödite.	+
121° 1′	Beryllonite.	−
121° 22′	Herderite.	−
121° 30′	Glaucochroite.	−
122° 48′	Mirabilite (red).	−
124° 40′	*Johnstrupite.*	+
125°	*Warwickite.*	+
125°	Xanthoconite.	−
126° 26′	Phosphosiderite.	+
127° 2′	Wavellite.	+
129° 32′	Scorodite.	+
132° 57′	Liroconite.	−
134° 27′	Acmite.	−
135° 26′	Prehnite.	+
136° 25′	Lazulite (red).	−
137° 7′	Trona.	−
151° 0′	Chessylite (blue).	+

Minerals arranged according to the value of 2V

36° 52′	Natrochalcite.	+
37° 34′	Hutchinsonite.	−
39° 30′	*Spurrite.*	−
40° 54′	Botryogen.	+
43° 30′	*Stellerite.*	
49° 46′	Edingtonite.	−
50°	*Pascoite.*	−
51°	Fayalite.	−
54° 3′	Crocoite.	+
57°	Spodumene.	+
58°	*Cebollite.*	+
58° 59′	Diopside.	+
59° 52′	Hedenbergite.	+
60°	Carpholite.	−
60°	*Custerite.*	+
60° 50′	Anglesite.	+
65°	Alamosite.	−
65°	Barylite.	+
67° 35′	Thalenite.	−
67° 54′	Humite.	+
68° 49′	Sapphirine.	−
69° 5′	Sulphur.	+
69½°	Stokesite.	+
69° 48′	Carnallite.	+
70°	Enstatite.	+
71° 10′	Blödite.	+
71° 56′	Jadeite.	+
72° 37′	Stibiocolumbite.	+
73° 10′	Vivianite.	+
73° 39′	Epidote.	−
74° 8′	Datolite.	−
74° 17′	Axinite (red).	−
74° 41′	Bertrandite.	−
75°	Hübnerite (red).	+
75° 58′	Stibiotantalite.	+
76° 6′	Tephroite.	−
76° 12′	Rhodonite.	−
76° 27′	Clinohumite.	+
76° 46′	Dawsonite.	−
76° 56′	Anorthite.	−
77° 4′	*Leucosphenite.*	+
78° 30′	*Gedrite.*	−
78° 36′	Kröhnkite.	−
78° 37′	*Wöhlerite* (red).	−
79° 3′	Hyalophane.	−
79° 40′	Chondrodite.	+
79° 46′	*Låvenite.*	−
79° 59′	Homilite (red).	+
80° 4′	Actinolite.	−
80° 38′	Heintzite.	+
80° 58′	Albite.	+
81° 8′	Libethenite.	−
81½°	*Didymolite.*	
81° 32′	Laurionite.	+
81° 40′	Clinozoisite.	+
82° 22′	Ludlamite.	+
82° 30′	Cyanite (red).	−
82° 37′	Caledonite.	−
82° 43′	*Gismondite.*	−
83° 5′	Thenardite (red).	+
83° 24′	Tilasite.	−
83° 29′	Trimerite.	−
83° 34′	Petalite.	+
83° 41′	Microcline.	−
84°	*Whewellite.*	+
84° 6′	Lawsonite.	+
84° 20′	Diaspore.	+
84° 30′	Andalusite.	−

84° 35′ Kainite. +	86° 13′ Melanterite. +	88° 46′ Anthophyllite. +
85° 28′ Gadolinite. +	86° 22′ Celsian. +	88° 46′ Staurolite (red). +
85° 52′ Harmotome. +	87° 17′ Hambergite. +	88° 54′ Olivine. +
86° Mesolite. +	88° 16′ Tremolite. −	90° Boracite.
86° 10′ Forsterite. +	88° 23′ Danburite. −	

TABLE IV

Minerals arranged according to their Specific Gravity

0·92 Ice.
1·03 *Copalite.*
1·07 *Elaterite.*
„ *Succinite.*
„ *Uintahite.*
1·10 *Libollite.*
1·44 Natron.
1·45 Teschemacherite.
1·48 Mirabilite.
„ Sassolite.
1·50 *Collyrite.*
„ Tschermigite.
1·53 Sal-ammoniac.
1·54 *Lansfordite.*
1·55 *Anthracite.*
„ Thermonatrite.
1·60 Carnallite.
1·61 Stercorite.
1·64 *Mellite.*
1·65 Bischofite.
„ Ulexite.
1·66 Aluminite.
1·68 Struvite.
1·70 Borax.
„ Alunogen.
„ *Boussingaultite.*
1·75 Kalinite.
„ Epsomite.
„ *Ettringite.*
1·76 Hexahydrite.
1·77 Mascagnite.
1·78 *Apjohnite.*
1·81 *Ihleite.*
1·84 Nesquehonite.
„ *Fibroferrite.*
1·87 Allophane.
„ *Chloropal.*
„ Inyoite.
1·88 Thaumasite.
„ *Mendozite.*
1·89 Melanterite.
„ Hannayite.
1·90 *Ascharite.*
1·92 *Faujasite.*
1·94 Gaylussite.
1·94 Boothite.
1·95 Halotrichite.
„ *Hydroboracite.*
1·98 Sylvite.
2·00 Goslarite.
„ *Sepiolite.*
„ *Erionite.*
„ Morenosite.
„ *Schrötterite.*
2·03 *Artinite.*
2·04 Melanophlogite.
„ *Diadochite.*
2·06 Kröhnkite.
2·07 *Hydrotalcite.*
„ Sulphur.
„ Botryogen.
2·08 *Mordenite.*
2·09 Coquimbite.
2·10 Gmelinite.
„ Deweylite.
„ Newberyite.
„ *Halloysite.*
„ Copiapite.
2·11 *Quetenite.*
„ Amarantite.
2·12 Chrysocolla.
„ Meyerhofferite.
„ Chabazite.
„ *Stellerite.*
„ Castanite.
„ *Quenstedtite.*
2·13 Kainite.
„ Nitre.
„ Trona.
„ *Levyne.*
„ Heintzite.
2·14 Salt.
2·15 Opal.
„ Picromerite.
„ Sideronatrite.
2·16 Graphite.
„ *Hydrogiobertite.*
„ Hydromagnesite.
„ *Stichtite.*
„ Stilbite.
2·17 Fluellite.
„ Römerite.
2·20 Heulandite.
„ *Hydrophilite.*
„ Darapskite.
„ Phillipsite.
2·21 Chalcanthite.
„ Brushite.
2·22 *Chrysotile.*
2·23 *Laubanite.*
„ *Whewellite.*
„ Natrolite.
2·24 *Cimolite.*
2·25 *Epistilbite.*
„ Blödite.
„ *Lindackerite.*
2·26 Nitratine.
„ *Zincaluminite.*
„ *Gismondite.*
„ Analcite.
2·27 *Saponite.*
„ Mesolite.
2·28 Okenite.
2·29 Pinnoite.
„ *Metabrushite.*
2·30 *Glauconite.*
„ *Hydronephelite.*
„ Scolecite.
„ *Jefferisite.*
„ Laumontite.
„ *Humboldtite.*
„ Tridymite.
„ Sodalite.
2·31 Chlormanganokalite.
2·32 Wellsite.
„ Gypsum.
„ Nosean.
2·33 Wavellite.
„ *Felsőbanyite.*
2·34 *Kehoeite.*
„ Rinneite.
2·35 Hambergite.
„ Cristobalite.
„ *Pitticite.*
„ Pirssonite.

2·35 Hydrargillite.
,, Apophyllite.
,, Thomsonite.
2·37 *Newtonite.*
,, Löweite.
2·38 Northupite.
2·39 Brucite.
2·40 Dawsonite.
2·41 *Genthite.*
,, *Pholidolite.*
2·42 Sulphoborite.
,, Lazurite.
,, Colemanite.
2·43 *Davyne.*
,, *Hautefeuillite.*
2·44 *Microsommite.*
2·45 Petalite.
,, Brewsterite.
,, Haüyne.
,, Cancrinite.
2·46 *Fischerite.*
,, *Pascoite.*
,, *Tychite.*
2·47 Harmotome.
,, *Hoernesite.*
,, Leucite.
2·48 Wapplerite.
2·49 *Phacelite.*
,, Sulphohalite.
,, Ussingite.
2·50 *Spadaite.*
,, Carphosiderite.
,, Peganite.
2·51 *Callainite.*
,, *Metahewettite.*
2·52 Kieserite.
,, Lucinite.
2·53 *Metavoltine.*
,, Chalcophyllite.
,, *Calcoferrite.*
2·54 *Connarite.*
,, *Sphærite.*
2·55 Epididymite.
,, Hewettite.
,, Eudidymite.
,, Bauxite.
2·56 Serpentine.
,, Hanksite.
,, Ferronatrite.
,, Microcline.
,, Orthoclase.
2·57 Marialite.
,, *Howlite.*
,, Milarite.
2·58 Anorthoclase.
,, Gyrolite.
,, Syngenite.
,, *Barrandite.*
2·60 Nepheline.
,, Elpidite.
,, Bertrandite.
,, Lanthanite.
,, Ralstonite.
,, Kaolinite.
,, Kaliophilite.
2·62 Chalcedony.
,, *Mizzonite.*
2·63 Vivianite.
,, *Zaratite.*
,, Cordierite.
,, *Elæolite.*
,, *Dipyre.*
2·64 Albite.
,, Aphthitalite.
2·65 Quartz.
2·66 Oligoclase.
,, Alunite.
2·67 *Rumpfite.*
,, Eucryptite.
2·68 Andesine.
,, Thenardite.
2·69 Beryl.
,, Hillebrandite.
,, Pharmacolite.
2·70 Talc.
,, *Collophanite.*
,, Scapolite.
,, *Bořickite.*
,, *Steatite.*
,, Augelite.
2·71 Labradorite.
,, *Didymolite.*
2·72 Meionite.
,, *Neotocite.*
,, Turquoise.
,, Calcite.
,, Pennine.
,, *Bavenite.*
2·73 Pectolite.
2·74 Alumian.
2·75 Clinochlore.
,, *Narsarsukite.*
,, Monetite.
,, *Hisingerite.*
,, Anorthite.
2·76 Phosphosiderite.
,, Glauberite.
2·77 *Wardite.*
2·77 Polyhalite.
,, Edingtonite.
2·78 *Astrolite.*
,, Cryolithionite.
2·79 *Voltaite.*
,, Villiaumite.
2·80 Hyalophane.
,, *Stilpnomelane.*
,, *Bazzite.*
,, Catapleiite.
2·82 Phlogopite.
2·83 Langbeinite.
,, Anapaïte.
,, Natrochalcite.
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ERRATUM

P. 284, Fig. 419. The words "3rd Order" should be placed over the letters "C_3 B_3".

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